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HFA-PFC Systems for Tactical Mobile Electric Power Systems

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CECOM Belvoir RD&E Center

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Tactical Mobile Electric Power Systems have the potential for significant weight savings. An average decrease of 87.2% may be achieved through the use of a high frequency alternator - power frequency converter combination, when compared to the standard 1800 rpm fixed speed 60 Hz generator. A potential 48.6% decrease is possible when considering the complete engine generator set. A gearbox provides the necessary speed increase for high speed/high frequency operation. This also provides an oil management system for cooling equipment and ultimately providing a higher power density system. Integration of additional functions, such as a starter generator, provides for added weight savings. The approach may be extended to a modular system concept to reduce the number of unique system components, and accommodate growth requirements. Additional new features such as variable speed operation of the engine may be integrated to reduce the average fuel consumption, acoustic emissions and IR emissions when operating at less then full load. This will assist in improving engine life span, and potentially reducing scheduled maintenance.

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A	Amperes
AC	Alternating Current
ACU	Alternator Control Unit
APU	Auxiliary Power Unit
BIT	Built-In Test
BLDC	Brushless DC (Machine)
DC	Direct Current
DoD	Department of Defense
EMC	Electromagnetic Compatibility
emf	Electromotive force.
EMI	Electromagnetic Interference
EP	External Power
HFA	High Frequency Alternator
IGBT	Insulated Gate Bipolar Transistor
IR	Infrared
kHz	Kilohertz
kW	Kilowatt
lb(s)	Pound(s)
MCT	Mos-Controlled Thyristor
MIES	Modern Imagery Exploitation System
MEPS	Mobile Electric Power Source
MSL	Mean Sea Level
NPS	Noninterruptible Power Source
pf	Power Factor
PFC	Power Frequency Converter
PM	Permanent Magnet
PM BLDC	Permanent Magnet Brushless DC
PMG	Permanent Magnet Generator
RMS	Root Mean Square
rpm	Revolutions Per Minute
SCR	Silicon Controlled Rectifier
SOA	Safe Operating Area
SRM	Switched Reluctance Machine
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Source
V	Volt
VA	Volt-Ampere
VRM	Variable Reluctance Machine
VSCF	Variable Speed Constant Frequency
VSTOL	Very Short Take-Off and Landing
VTOL	Vertical Take-Off and Landing
W	Watt
XFMR	Transformer

1. SUMMARY

Application of a High Frequency Alternator - Power Frequency Converter (HFA-PFC) System can substantially reduce Tactical Mobile Electric Power Source weight and size. An 87.2% average weight reduction is anticipated over the existing electric generators in the 5 to 1000 kW power levels. A 46.6% average weight reduction is possible for the engine generator sets over the same power level range. The engine generator set may accrue an additional weight savings of approximately 2% when using an integrated starter generator approach. These estimates are inclusive of all equipment necessary to operate the HFA-PFC System. These results warrant further exploration of the concepts through prototype hardware design, development, and demonstration.

The majority of weight savings is attributed to the use of a high frequency alternator. Nominal operating frequencies as high as 2 kHz are achievable by increasing the generator base speed with a gearbox. Machine technology including switched reluctance, wound rotor brushless DC, and permanent magnet allow the design of high power density generators. An oil management system is integrated with the gearbox to provide lubrication for the gearbox and HFA bearings, and cooling for the gearbox, HFA and PFC. Operating frequencies above this range start to exhibit diminishing returns due to increased machine losses.

The PFC may intrinsically provide many functions with little or no hardware modifications. A time limited uninterruptible power supply architecture is possible and essentially inherent when a starter generator configuration is used. The PFC may be used as a local power conditioner, operating off a foreign utility grid. The engine and HFA would become a backup source of power in the event of the grid failure.

The work performed during this effort is applicable to unique designs for each power level or to a modular system approach. A modular approach will accommodate different functional options, and the application of standard equipment designs to a range of power levels. The weight analysis is based upon the modular concept. There is approximately a 15% penalty in HFA-PFC System weight to implement the modular approach. This is associated with less then a 1.3% impact when considering the engine generator set as a whole.

Variable speed operation of the engine and HFA will provide increased engine and HFA life expectancy, reduce fuel consumption, and reduce acoustic and IR signatures of the equipment. Potential increases in scheduled service intervals may be experienced which will contribute to lower life cycle costs.

Future technologies may easily be integrated with an HFA-PFC approach as they mature. This is due to the modular architecture of the system, and being able to evolve only affected portions of the design. New power semiconductor technology such as silicon carbide will improve PFC efficiency and will increase thermal design margins on the component application. Smart power systems may eventually provide load scheduling and mission reconfiguration for automated operation.

The work performed under this project addressed reducing size and weight of mobile tactical engine generator sets to improve mobility and deployability. Mobility will be improved through a direct weight reduction of the equipment being towed or transported. Deployability will be improved through lower payloads and smaller size allowing faster and larger deployment with cargo aircraft transport.

Power levels from 0.5 to 1000 kW were addressed in this project. The work comprised all required components from the engine interface to the electrical output terminals of the engine generator set. Support of the existing equipment infrastructure was integrated into the overall analysis.

2. INTRODUCTION

2.1. TACTICAL POWER GENERATION BACKGROUND

Advanced electrical power generation techniques are required to support a new Army goal of highly dynamic conflicts. As the battle theater definition evolves to include "shoot and scoot" scenarios, support equipment must embrace the new requirements and specifications. A high degree of mobility and deployability is required for using power generation equipment with new highly mobile tactical weapons systems. Additionally, as the battlefield becomes "more electric", a growing demand for electrical generation capacity exists while improving mobility. Increased capability of enemy target acquisition and fire control systems has necessitated more stringent technical requirements on acoustical emissions and infrared signatures.

Traditionally, this type of power generation requirement has been satisfied by Tactical Power Generation Sets. As defined in MIL-STD-1332, Tactical type includes "generator sets designed for high mobility in direct support of military forces where output of generator sets is normally, but not exclusively used at generated voltage....... Life characteristics are considered secondary to light weight, small size, and a high degree of mobility".

Typical existing equipment includes a 60 Hz generator operating at 1800 rpm. This approach restrained the electromagnetic design of the generators with the compromise of weight. The electromagnetic design size is inversely proportional to its operating frequency for a given power. In a synchronous machine, frequency can be directly related to rotor or shaft speed, and the number of pole pairs. A substantial size and weight savings may be realized by operating the generator at high speeds. In order to accomplish this, a power converter is required to condition the output power of the system to a useable 60 Hz, regulated voltage.

Further reductions in generator set weight may be accrued by integrating common functions of the new power generating system and the engine. One such opportunity is to eliminate the starter, and use the generator controlled and powered by the power converter.

Other areas for improvements include engine and generator operating life, fuel consumption, acoustical and IR signatures. These may be addressed by a common factor of reducing average engine speed. The use of a high frequency alternator and a power converter can allow the engine speed to vary dependent upon electrical utilization load. Existing generator equipment is operated at a fixed speed independent of load. At light and varying loads, this can reduce efficiency and increase fuel consumption, emit stronger signatures, and reduce equipment life.

The potential weight savings will bring substantial benefits to troop mobility and deployability. This can be significant when considering air transport of rapid deployment forces. Cargo aircraft and troop transport are restricted by payload capability for basic transport as well as operating in VTOL/VSTOL environments. Any weight savings on air cargo can directly increase the amount of equipment being transported, and results in improved mobility. Additionally, the logistical support of the equipment will be reduced by increased fuel efficiency, and can be further enhanced by designing common standardized modules, where spares service several power levels.

The high speed generator alternative can be met with a High Frequency Alternator (HFA) coupled with a Power Frequency Converter (PFC). New and future developments in high power electronics make the HFA-PFC approach a cost effective, technically viable alternative for highly mobile, tactical power generation units. The variable engine speed operation may be met by using the HFA-PFC in a Variable Speed Constant Frequency (VSCF) configuration. This allows the engine speed, and subsequently the generator frequency to vary dependent upon load, while producing a high quality - fixed frequency, regulated voltage output. The advanced technologies and future technology trends now offer alternatives to the traditional fixed-low speed generators currently in use.

2.2. PROJECT PURPOSE

This project was undertaken to explore the potential for generator set size and weight reduction through the use of integrated power components with mobile engine generator sets. The primary focus is on the use of engine driven High Frequency Alternators combined with Power Frequency Converters to provide military standard output power.

2.3. PROJECT SCOPE

The scope of the project is to define optimum HFA-PFC System architectures, PFC topologies, HFA technologies, and identify optimum power semiconductor technologies. The definitions are applicable to the power generation range of 0.5 kW to 1000 kW. The characteristics of primary concern during evaluation of the various technologies, architectures, and topologies are: size and weight, performance, and cost. Performance includes functional capability, power quality, efficiency, and reliability.

The project essentially covers from the HFA shaft input to the PFC output connections and its interface with a conventional internal combustion engine prime mover. Alternative prime movers, or other raw power sources such as a fuel cell or photovoltaic array are not included in this work.

The work is targeted at the stand alone mobile engine generator set - man transportable or mounted on a towable trailer. Much of the results are directly applicable to other types of installations such as an integrated power unit housed in a command center trailer such as the Modern Imagery Exploitation System (MIES), or a power generation system integrated with a vehicle drive engine.

Limited computer analysis was determined to have beneficial input to the results, and therefore, was included as part of the work. Computer simulations were not a requirement of this project.

The range of technologies evaluated includes technology that is currently available for integration into near term production hardware, to technologies that may be integrated in the future as they mature.

2.4. REPORT ORGANIZATION

An overview of the approach used to conduct the research, assumptions made during the work, and procedures for completing each major task in the project are presented in section 3. Section 4 gives detailed discussions of the results for each major project task. The material of each subsection in section 4 is typically arranged in a common format: beginning with a summary of the task results, followed by a tabular compilation of alternative comparisons, then concluded with a review of the information and data collected with respect to that task. Extensive supporting data is located in referenced appendixes where applicable. The subsection organization of section 4 follows the format and schedule of the original project tasks. Section 5 presents conclusions resulting from the work tasks. Recommendations for continued work and areas to focus future development efforts are described in Section 6.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1. APPROACH

The overall approach to this project was to evaluate a variety of advanced technology alternatives for electrical power generation as defined by the scope of this project. In general, a review of the functional and performance requirements established the baseline requirements to which equipment must perform. Then addressing the requirements from a system top level down approach, alternative techniques were reviewed and evaluated. This approach was accomplished by subdividing the project into the following major tasks:

1. Requirements Definition
2. HFA-PFC System
3. PFC Topology
4. HFA Technology
5. Engine Interface
6. Power Semiconductor
7. Cooling and Packaging

Alternative technologies in each task were evaluated based upon comparing the following primary criteria: size, weight, functional performance, and cost.

While it is the primary purpose of this project to explore ways to reduce generator set size and weight to improve troop mobility, it is also important that these approaches be able to support the existing infrastructure of utilization equipment. This requirement was addressed by satisfying the existing military standards and specifications. For example, the generator set output should be field reconnectable for different output voltage configurations as the immediate application requires.

Much of this effort was an iterative process. Even though the report is organized in a particular order, some information generated in later sections is fed back into earlier sections.

Circuit simulations were performed on several topologies reviewed under the PFC task. The purpose was to verify operational capability of certain topologies and to compare performance characteristics such as output harmonic content, filter currents, and switching stresses of certain topologies. Microsim PSPICE, version 6.1a, based upon the University of California at Berkeley SPICE2G.6 was used to perform the simulations. This is a current version, released in September 1994, and is capable of mixed analog/digital circuit simulation with an extensive library of discrete components and analog behavioral models.

The computer models and simulations used during this project have formed a foundation for continued modeling and integrated modeling during a detailed design phase. The PSPICE software will allow integration and simulation of all system components. PSPICE has the ability to model systems using analog behavioral modeling techniques which may be combined with discrete circuit modeling. This capability allows the integration of electronic circuits and electromechanical systems for computer simulation.

The foundation for much of the work based upon aerospace electric machine applications. These designs typically represent state-of-the-art technology since aerospace applications are very concerned with weight. This approach also provides a good base to evaluate future trends in technology application. Space based power generation systems were considered and viewed as future potential since these are usually limited to one of a kind installations with a very high associated cost.

3.2. ASSUMPTIONS

A general assumption was that reasonable changes to the engine could be accommodated. These are typically not significant modifications and may include removal of the existing DC starter, or that engines may be operated at a variable speed, etc. No major redesigns of the engines would be necessary to use the HFA-PFC approach.

A general guideline was used to evaluate the weight of existing generators since there is such a wide expanse of possible engines and 60 Hz generators for a given power level. Present mobile engine generator sets have a weight distribution of approximately 1/3 to each major component - the generator, the engine, and the trailer. Excluding the trailer, the engine/generator weight distribution is approximately equal (50% / 50%) for a set on rails. This assumption was validated with data on several engine generator sets where the division was actually 47.6% and 52.4% for the engines and generators respectively. The sample dispersion was very tight having a standard deviation of 0.54.

For the purposes of this report, the term Mobile Electric Power Sources (MEPS) is defined to mean a engine generator set mounted on a trailer. The phrase "engine generator set" or "generator set" implies a prime mover or engine, and a 60 Hz generator or a HFA-PFC System to provide fixed 60 Hz output. The "engine generator set" or "generator set" is mounted on support rails. The difference in terminology is most important when evaluating weights, and is indifferent most other times.

The definition of power density for this report is defined as weight per unit power. In most instances it is in pounds/kilowatt (lbs/kW). This convention was used since much existing data of power density is in this format.

3.3. PROCEDURES

The following procedures describe some of the detailed steps used in performing each major task in the project.

The Requirements Definition Task was used to define performance and operational requirements for the tactical power generation equipment covering the identified power ranges in this study. This task consisted of reviewing existing specifications including:

MIL-STD-633E	Military Standard Mobile Electric Power Engine Generator Standard Family General Characteristics
MIL-STD-1332B	Definitions of Tactical, Prime, Precise, and Utility Terminologies for Classification of the DoD Mobile Electric Power Engine Generator Set Family

The review determined such parameters as ambient operating environment, output power quality requirements, and output power characteristics and configuration.

A Phase I kick-off meeting was held with the Army at CECOM, Fort Belvoir, Virginia in order to present the work plan outline, and ascertain that the work plan was properly targeted with emphasis placed on appropriate evaluation criteria. Additionally, some information gathered under this task was derived from telephone contacts with the CECOM, Fort Belvoir Research Development and Engineering Center.

Past studies were referenced to assess the evolution of requirements and establish additional foundations. Some of these reports include:

POWER CONDITIONING EQUIPMENT AVAILABILITY SURVEY
Report 2395, December 1983, DTIC
W. David Lee
US Army Belvoir Research & Development Center

The primary purpose of HFA-PFC System task was to develop and compare several top level HFA-PFC system architectures. The major elements of this task included interpreting the requirements established in the previous task, developing alternative architectures and creating a matrix of applications, and reviewing the architectures for the various power ranges. Block diagrams of the various system architectures were generated to support the evaluations. A variety of texts, technical journals and papers, and experience were consulted to perform this task.

The PFC Topology Optimization task reviewed numerous techniques of solid state power conversion as alternatives for the PFC topology. A matrix of applications was generated to select candidate topologies. A comparison table was compiled to provide a tabulation of general information regarding each topology. General descriptions of the alternative topologies was provided with the associated block diagrams. The PFC approaches were compared against the selection of the HFA-PFC System architectures to assure the topology is suited for application in the respective architecture. Trade-offs included functionality, flexibility, complexity, component stress, size, and weight.

The HFA Approach Optimization task was organized in the same fashion as the PFC Topology Optimization task. An application table and a matrix of technology comparisons were created. A review of electric machine technology was performed. The major characteristics considered included size, weight, functionality, reliability, performance, and cost.

The Engine Operation Review task reviewed typical engine operating characteristics and evaluated potential features that could be integrated with the HFA-PFC System to enhance overall performance. Engine interface requirements such as a gearbox are addressed under this task. Functions that could be integrated for economies of scale were considered highly important as they have the potential to assist in achieving the overall project goal.

A review of Power Semiconductor technology was done. This included evaluating the potential applications for presently available devices, and projecting future power semiconductor developments and evaluating their potential applications.

An integral part of the HFA-PFC System is the Cooling and Packaging approach. The results of this task reviewed various approaches to further enhance technical advances. This is a summary of options, with specifics on the PFC and HFA included in their respective subsections.

4. RESULTS AND DISCUSSION

The results and discussion subsections presented in this section correspond to the major work tasks identified in the work breakdown structure for this project.

4.1. REQUIREMENTS DEFINITION

The requirements definition task has established the baseline operational and performance requirements for the equipment. During this task, evaluation criteria were also established and ranked in importance to assist in selecting the optimum configurations and technologies as the project progressed.

A review of existing specifications and evolving US Army field requirements has developed a general set of requirements for a standard family of advanced lightweight tactical power generation units. These include:

- Addressing power generation from 0.5 kW to 1000 kW
- Providing multiple power output configurations and voltages
- Operating typically over the ambient temperature range of -25° F to 125° F
- Operating in the typical altitudes of Mean Sea Level to 8000 feet

Various technologies were evaluated to satisfy the above general requirements with respect to size, weight, performance (including power quality, efficiency, reliability, and handling requirements), cost, electromagnetic compatibility, and acoustic noise signatures. This subsection establishes the minimum acceptable standards and performance requirements for evaluating the various technologies.

4.1.1. EXISTING SPECIFICATION REVIEW

Numerous military standards and specifications are applicable to the tactical generator sets. A review of the relevant specifications provides a foundation for much of the design requirements and the comparisons with existing technology. A summary of the relevant material is provided here as reference.

MIL-STD-1332B ***Definitions of Tactical, Prime, Precise, and Utility Terminologies***

MIL-STD-1332B defines classifications of equipment based upon use and capability. These classifications must be fulfilled by equipment designed to operate in the power levels of this study. Classifications are subdivided into three main categories. The ***type***, describing the equipment application and intended use. The ***class*** defining electrical performance characteristics. The ***mode*** defining the output power type.

1. TYPE

a) **Tactical -** Designed for high mobility in direct support of military forces. No electrical transformation or extensive distribution system is used.

Ranking of characteristic importance:

(1) Light weight
(2) Small size
(3) High degree of mobility
(4) Reliability
(5) Life

b) **Prime -** long term use in semi-fixed locations for extended periods of time. High voltage output for distribution, requires transformation.

Ranking of characteristic importance:

(1) Long life
(2) Reliability
(3) Size
(4) Weight
(5) Mobility

2. CLASS

a) **Class 1 - Precise --** Close control of voltage and frequency performance for critical applications.

b) **Class 2 - Utility --** power for general purpose applications. Three grades which are compatible with commercial power. (2A, 2B, 2C)

3. MODE

a) **Mode I --** 50/60 Hz capability

b) **Mode II --** 400 Hz

c) **Mode III --** 60 Hz only

d) **Mode IV --** DC output only

The standard details the electrical performance characteristics of the generator sets as shown in Tables 1 and 2. The characteristics for the Precise Class of equipment are shown for simplicity since these are the tighter regulation tolerances and faster transient responses that will be required.

Table 1. Electrical Performance Characteristics; AC

AC Characteristic	Precise (Class 1)	Test Method (MIL-STD-705)
Voltage Characteristics		
Regulation (%)	1	608.1
30 sec stability (% BW)	1	608.1
Transient Performance		
Load application		
Dip (%)	15	619.2
Recovery (sec)	0.5	619.2
Load Removal		
Overshoot (%)	15	619.2
Recovery (sec)	0.5	619.2
Motor Load (2 PU current) 5 kW < x <500 kW gen set		
Dip (%)	30	619.1
Recovery to 95% (sec)	0.7	619.1
Waveform (3ϕ, add 1% for 1ϕ)		
Max. Deviation (%)	5	601.1
Max. Ind. Harmonic (%)	2	601.4
Voltage Unbalance (%), unbalanced load	5	620.2
Phase Balance Voltage (%)	1	508.1
Voltage adjustment (% min)	-5, +17	511.1
Frequency Characteristics		
Regulation (%)	0-3	608.1
30 sec stability (% BW)	0.5	608.1
Transient Performance		
Load Application		
Undershoot (%)	4	608.1
Recovery (sec)	2	608.1
Load Removal		
Overshoot (%)	4	608.1
Recovery (sec)	2	608.1
Frequency Adjustment (% min)	+/- 3	511.2

Table 2. Electrical Performance Characteristics, DC

DC Characteristic	Utility (Mode IV)	Test Method (MIL-STD-705)
Voltage Characteristics		
Regulation (%)	4	608.1
Steady state stability (% BW)	2	608.1
Transient Performance		
Load application		
Dip (%)	30	619.2
Recovery (sec)	2	619.2
Load Removal		
Overshoot (%)	40	619.2
Recovery (sec)	2	619.2
Ripple Voltage (%)	5.5	650.1
Voltage Adjusting Range	23 to 35 @ norm amb +/- 5% @ extreme temp	511.1

Power generation capacity is derated with respect to specific equipment power ranges and operating altitude. Table 3 shows the applicable temperature ranges for various power levels and types of engines.

Table 3. Generator Set Derating for Altitude and Temperature

DoD Standard	*Capacity at Various Environmental Conditions*				
kW Rating	*MSL, -25 °F to +125 °F*	*MSL, -65 °F to +125 °F*	*1500 ft, 90 °F*	*5000 ft, 107 °F*	*8000 ft, 95 °F*
0.5, 1.5 kW reciprocating engine driven	Rated kW	N/A	Rated kW	Rated kW	90% Rated kW
3 thru 200 kW reciprocating engine driven & gas turbine engine driven (GTED)	Rated kW	Rated kW	Rated kW	Rated kW	90% Rated kW
Above 200, thru 750 kW reciprocating engine driven	Rated kW	N/A	Rated kW	80% Rated kW	75% Rated kW
Above 200, thru 750 kW GTED	Rated kW -25°F to +60°F; 70% rated kW to +125°F	N/A	90% Rated kW	75% Rated kW	70% Rated kW

The extreme lower temperature limit of -65 °F for operation of equipment in the 3 kW thru 200 kW range is important when evaluating power semiconductor and component applications in PFC designs.

MIL-STD-1332 also details the voltage connections and possible output configurations as defined in Figure 1.

STANDARD VOLTAGE CONNECTIONS

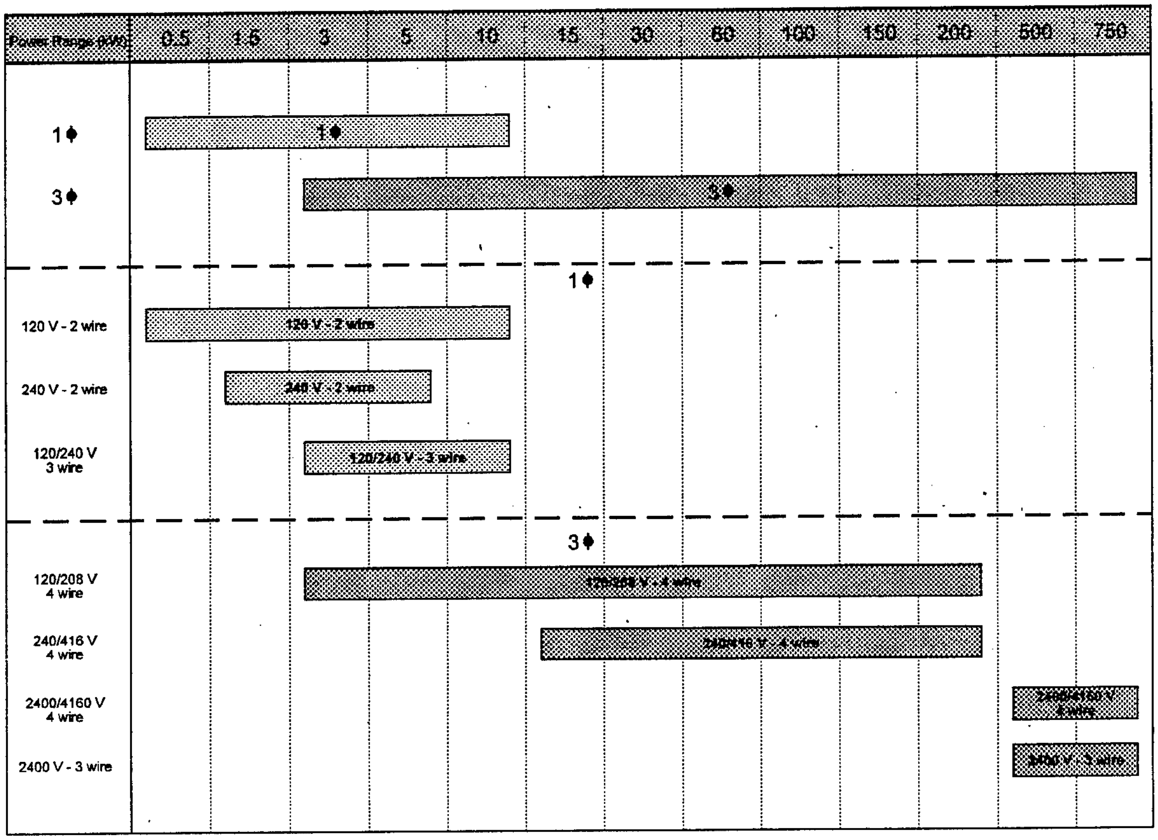


Figure 1. Standard Voltage Connection Requirements

Figure 1 illustrates the flexibility required in the HFA-PFC output in order to accommodate various output configurations and voltage levels. In each of the standard family power levels that cross more then one configuration, the output must be capable of supporting the different configurations or different output voltages. The reconnections, e.g. from 1ϕ to 3ϕ, or from 120 V - 2 wire to 240 V - 2 wire, must be provided for in the field.

Based on the assumptions of weight distribution defined earlier under the Assumptions section, and the specification weights according to MIL-STD-1332, estimated power densities are shown in Table 4.

Table 4. Estimated Power Densities

kW Rating	Maximum Dry Weight	Power Density (lb/kVA) GEN SET	GEN*	ENG*
0.5	100	200.0	104.7	95.3
1.5	150	100.0	52.4	47.6
3	300	100.0	52.4	47.6
5	1100	220.0	115.2	104.8
10	1400	140.0	73.3	66.7
15	3000	200.0	104.7	95.3
30	3500	116.7	61.1	55.6
60	5000	83.3	43.6	39.7
100	7000	70.0	36.6	33.4
150	9000	60.0	31.4	28.6
200	10500	52.5	27.5	25.0
500	32000	64.0	33.5	30.5
750	32000	42.7	22.3	20.3

* Power density assumes a 52.4% /47.6% weight division between the generator and the engine respectively. Actual data confirmed the approximations. The weights given are the maximum allowable for an engine generator set on rails based upon MIL-STD-1332.

The actual existing generator set weights as given in MIL-STD-633 tracked the maximum allowable weights of the specification fairly close. The maximum weights per MIL-STD-1332 are plotted in Figure 2 for reference.

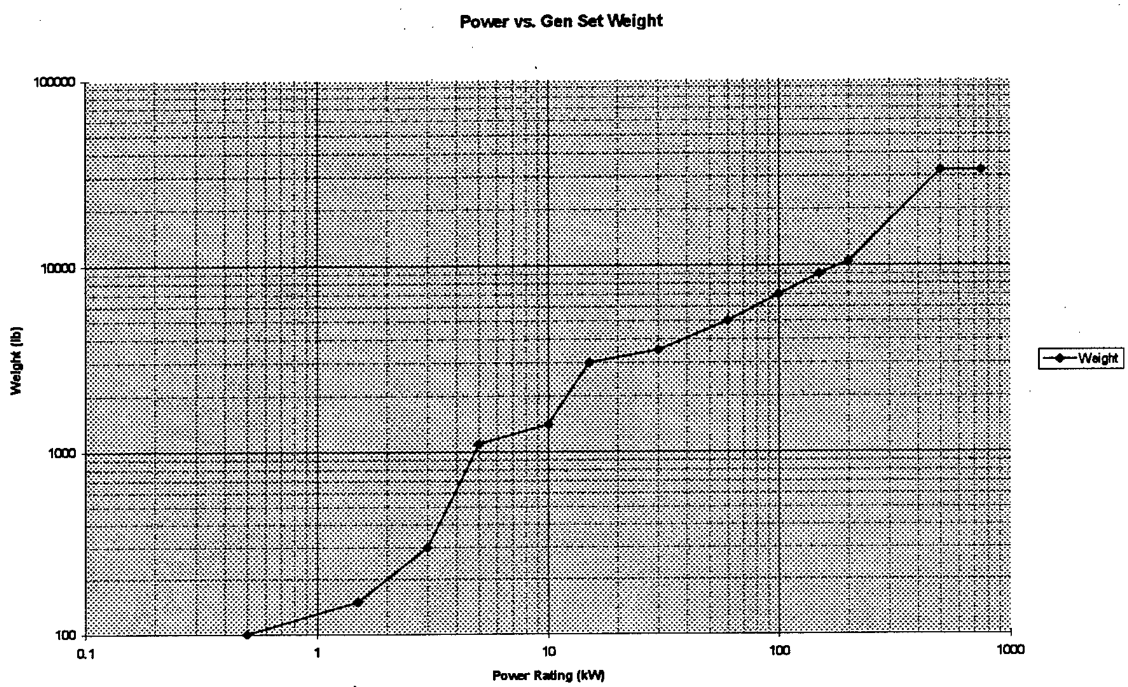


Figure 2. Maximum allowable Engine Generator Set Weights

MIL-STD-633E *Mobile Electric Power Engine Generator Standard Family Characteristics*

This standard provides details on the physical and electrical characteristics for each member of the existing DoD approved family of mobile electric power engine driven generator sets.

The data collected from this standard is presented in tabular form in Appendix A.

Several applicable observations were made from the standard family characteristics:

- Rope start, or manual start, is available on engines up to the 10 kW power range.
- Electric start is available on gas engines starting at 5 kW. Electric start is standard on all diesel engines down to the minimum 5 kW power level.
- Liquid cooled engines are fairly standard at 15 kW and above.

Since these characteristics represent typical engine applications, the technologies being addressed in this project must be capable of integrating with the appropriate engine qualities such as electric start functions, hot battery backups, and shared functions like cooling and control.

4.1.2. PHASE I LAUNCH MEETING

A coordination meeting was used to confirm certain aspects of the project. These included the scope of power ranges to be covered, and the evaluation criteria.

The scope of the applicable power range was expanded to cover 0.5 kW to 1000 kW from the original 5 kW to 1000 kW. Two factors contributed to the expansion. CECOM identified that tactical generator sets frequently cover power levels as low as 1.5 kW, and MIL-STD-1332 covers the power ranges from 0.5 kW to 750 kW. These ranges combined with the modular concepts being explored set the low power level down to 0.5 kW.

Mobile tactical equipment typically encompasses 1.5 kW to 60 kW power levels. Man-portable hardware is defined to include 0.5 kW to 3 kW, and typically less then 120 lbs. With the growth of the electronic battlefield, transportability and deployability must be considered for power levels up to 1000 kW, as seen with Ground Based Radar (GBR) systems.

Part of the requirements definition includes the evaluation criteria used to assess the various technologies and system architectures. That is the ability, or the requirement, of the technology to satisfy certain criteria. This criteria has been identified as follows:

1. Weight
2. Size
3. Performance
   a) Power Quality
   b) Efficiency
   c) Reliability
   d) Functionality
   e) Logistical Support
4. Electromagnetic Compatibility
5. Acoustic Noise Signatures
6. Infrared Signatures
7. Cost

Criteria 1 & 2 are usually closely linked and demonstrate a positive interdependence. The evaluation criteria ranking should be used as a guide. Specific power ranges may experience varying degrees of importance for the criteria.

4.1.3. ADDITIONAL REQUIREMENTS ASSESSMENT

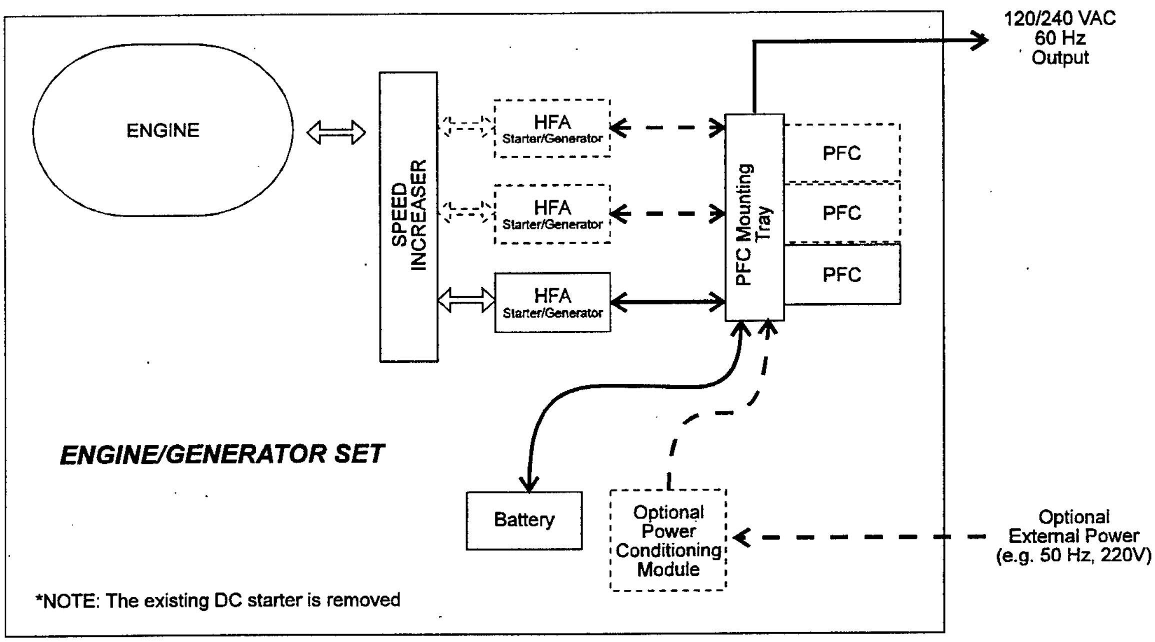
A report entitled "*POWER CONDITIONING EQUIPMENT AVAILABILITY SURVEY*" detailed the results of a study to identify a family of electric power conditioners that would complement the DoD standard family of Mobile Electric Power Sources (MEPS) with eight units ranging from 1.5 kW to 200 kW. The original intent appears to be using the power conditioner in series with the existing MEPS. The report provided some foundation as to alternative uses of the PFC equipment evaluated during this project. This report outlined a potential requirement for developing hardware that has an integrated power conditioning function.

Additional considerations were given to enhancing the functionality of the HFA-PFC system. Reviewing functions that may be integrated within the HFA-PFC baseline design by virtue of the intrinsic design will assist in diluting acquisition costs of the hardware, and further improving the power generation and functional capability to weight ratio.

4.2. *HFA-PFC SYSTEM*

Establishing baselines for the High Frequency Alternator - Power Frequency Converter (HFA-PFC) System was necessary to define the requirements for the individual HFA and PFC evaluation criteria. This process is essentially a top down approach in order to define the optimum system configuration and features that should be incorporated into the design in order to reduce weight and size, and in some areas provide additional functions. As work was performed on the individual PFC and HFA technologies, the resultant information was fed back to optimize the system.

A top level block diagram for an HFA-PFC System covering the 20 to 60 kW power range is shown in Figure 3. This is representative of the general HFA-PFC System Architecture. Slight variations for the different power ranges may be encountered, such as the number of parallel modules comprising a system. The suggested modular approach is the basis for the subdivisions of power ranges. Each power range has a base module for both the HFA and PFC.



Dotted line blocks represent modular units or optional units

Figure 3. General HFA-PFC System Block Diagram

A summary of the HFA-PFC System architectures with suggested features is presented in Table 5. The modular approach allows for a building block concept. The HFA and PFC modules are capable of operating in a paralleled configuration respectively to provide increased output capability, and the subsequent coverage of higher power output requirements. The main foundation for this approach is to develop a standard set of hardware that will assist in reducing logistical support of missions. For instance a spare 20 kW PFC or HFA base unit will provide spare replacement of the 20, 40, or 60 kW MEPS. The modular approach also provides opportunities to custom configure outputs if both AC and DC power are required. It also allows integration of add-on features such as power conditioning interface units, allowing the MEPS to operate as a foreign power utility grid - power conditioner. The modular approach is more fault tolerant and can continue operation at derated output during certain modes of PFC or HFA faults.

A Variable Speed Constant Frequency (VSCF) operation, where the generator and engine are controlled to operate over a speed range dependent upon load is optimum for all categories. Certain challenges may be encountered in the higher power categories where the engine response time slows significantly due to its effective moment of inertia and acceleration capability. Many system dynamics are encountered when operating in this mode including transient response capability of the engine, the HFA, and the PFC. This is one of the reasons behind including power management in the 500 - 1000 kW range. Power management will help to assess load demand as a leading function in the engine speed control algorithms.

The Noninterruptible Power Supply (NPS) capability is intrinsic to the modular design since paralleling logic and capability is required to support the modular operation of PFCs connected in parallel. NPS refers to the ability of MEPS to operate in parallel, connected to a common load bus.

The Uninterruptible Power Supply (UPS) is also intrinsic once a battery is included with the MEPS to provide starter power, whether or not using a starter/generator configuration. The UPS provides a hot back power source eliminating any brownouts or momentary loss of power due to primary engine shutdown. This is a time-limited power source based upon battery capacity and state of charge.

Some of the HFA-PFC System integral functions will assist in reducing the net weight of the MEPS. The starter/generator function eliminates the existing DC starter used on the primary engine for engine start. The electric motor capability is an intrinsic capability of the HFAs considered. The PFC by nature can supply the required excitation to control the motor as a starter with additional control algorithms when used with a switched reluctance electric machine.

The additional functions will also reduce the logistics of deployment. For instance, providing an integrated power conditioning function will allow the use of the local power grid in the theater of operation while reduce the operating time of the engine to produce 60 Hz, regulated electrical power. Even though the added function has a slight additional weight associated with it, it reduces the overall weight of equipment that would normally have to be transported to perform the same functions. Additionally, these functions can be supplied while still providing a significant weight reduction to the tactical MEPS.

Estimated System Weights

A summary of the HFA-PFC System Weight Predictions is presented in Table 6. All weights are given in pounds (lbs). This tabulation and comparison addresses all components required to implement the baseline modular HFA-PFC System and integrate it with a MEPS engine.

The ***"Total HFA-PFC System Weight"*** represents the comprehensive weight required to implement each power level. It should be noted the gearbox weight is identical across the power levels corresponding to one category. The reason is to use only one gearbox, and standardize the gearbox across the category. More discussions on the gearbox may be found under the Engine Interface Section of this report.

The comparison of weights is made based on generator set weights identified in MIL-STD-633. The estimated generator weights are based upon the general rule for generator/engine/trailer weight distribution described is the assumptions section of this report. The weights derived from MIL-STD-633 are actual hardware weights without a mobile trailer. These track fairly close to the specification, MIL-STD-1332, maximum weights for each power level.

The ***"Projected Weight Savings Over 60 Hz Generator"*** and ***"(%) SAVINGS"*** represent the predicted weight savings of electrical power production equipment only. That is, the HFA-PFC savings over the 60 Hz generator.

The ***"(%) TOTAL GEN SET SAVINGS"*** refers to the potential weight savings associated with a Generator Set on rails.

It should be noted that weight savings attributed to the removal of the DC starter was not included in these estimations. It may be estimated at approximately 2% of the engine generator set weight. This would increase the ***"(%) TOTAL GEN SET SAVINGS"*** by 2%.

Table 5. Optimum HFA-PFC System Architectures and Features for Various Power Ranges

	POWER RANGE					
FEATURE	***0.5 kW***	***1.5 - 3.0 kW***	***5 - 15 kW***	***20 - 60 kW***	***100 - 200 kW***	***500 - 1000 kW***
SYSTEM ARCHITECTURE	– Modular (base module for 1.5 kW inverter)	– Modular – 1.5 kW Base Unit – 2 Parallelable Units 1.5/3.0	– Modular – 5 kW Base Unit – 3 Parallelable Units 5/10/15	– Modular – 20 kW Base Unit – 3 Parallelable Units 20/40/60	– Modular – 100 kW Base Unit – 2 Parallelable Units 100/200	– Modular – 500 kW Base Unit – 2 Parallelable Units 500/1000
VSCF	– Variable Speed Constant Frequency	– Variable Speed Constant Frequency	– Variable Speed Constant Frequency	– Variable Speed Constant Frequency	– Variable Speed Constant Frequency	– Variable Speed Constant Frequency
STARTER/ GENERATOR			– Starter/Generator	– Starter/Generator	– Starter/Generator	– Starter/Generator
NONINTERRUPTIBLE POWER SOURCE			– Noninterruptible Power Source	– Noninterruptible Power Source	– Noninterruptible Power Source	– Noninterruptible Power Source
UNINTERRUPTIBLE POWER SOURCE			– Uninterruptible Power Source	– Uninterruptible Power Source	– Uninterruptible Power Source	
BATTERY CHARGE			– Battery Charge	– Battery Charge	– Battery Charge	– Battery Charge
EXTERNAL POWER CONDITIONING			– External Power Conditioning (Optional Module)	– External Power Conditioning (Optional Module)	– External Power Conditioning (Optional Module)	
POWER MANAGEMENT						– Power Management

Table 6. HFA-PFC System Weight Predictions Summary

COMPONENT	POWER LEVEL (kW)												
	0.5	1.5	3	5	10	15	20	40	60	100	200	500	1000
Power Frequency Converter	4	9	27	13	26	39	26	52	78	207	414	1040	2080
High Frequency Alternator	3	7	14	11	22	33	27	54	81	94	188	400	800
Gearbox & Mounting	3	10	10	25	25	25	45	45	45	150	150	500	500
Equipment Rack/Mounting	1	5	5	10	10	10	16	16	16	40	40	90	90
Oil Cooler				5	5	5	8	8	8	25	35	55	55
Fan	0.5	1	2										
Misc	0.2	1	1	2	2	2	3.2	3.2	3.2	8	8	18	18
Total HFA-PFC System Weight	11.7	33.0	59.0	66.0	90.0	114.0	125.2	178.2	231.2	524	825	2103	3543
MIL-STD-633 Calculated	44.5	65.4	149.2	371.2	444.3	1,282.7	1500	1900	2,235.6	3,664.9	5,497.3	18,337.5	30000
Generator Weights							est	est					est
Projected Weight Savings	32.8	32.4	90.2	305.2	354.3	1168.7	1374.8	1721.8	2004.4	3140.9	4672.3	16234.5	26457.0
over 60 Hz generator													
(%) SAVINGS	74%	50%	60%	82%	80%	91%	92%	91%	90%	86%	85%	89%	88%
MIL-STD-633 GEN SET Wt	85	125	149.2	709	848.7	2450	2700	3500	4270	7000	10500	35025	52000
							est	est					est
(%) TOTAL GEN SET SAVINGS	39%	26%	60%	43%	42%	48%	51%	49%	47%	45%	44%	46%	51%

4.2.1. REQUIREMENTS INTERPRETATION

An interpretation of the specifications and requirements is necessary to assure the HFA-PFC System and its subcomponent HFA and PFC, along with any support components, will perform satisfactorily. The majority of the requirements were identified and outlined in the "Requirements Definition" section of this report.

An important criteria is the ability to support the existing infrastructure of equipment in the field. One of the current requirements previously outlined is shown in Figure 4. This diagram shows the existing specification requirements, and the expanded range of capability by using a Modular HFA-PFC System Architecture. Field reconnection of output wiring configuration allows the generating system to be compatible with a wider variety of utilization loads. The modular approach expands the range of reconfiguration since the base module design must accommodate the reconfigurability. This is now available across all applicable power levels associated with that particular base module.

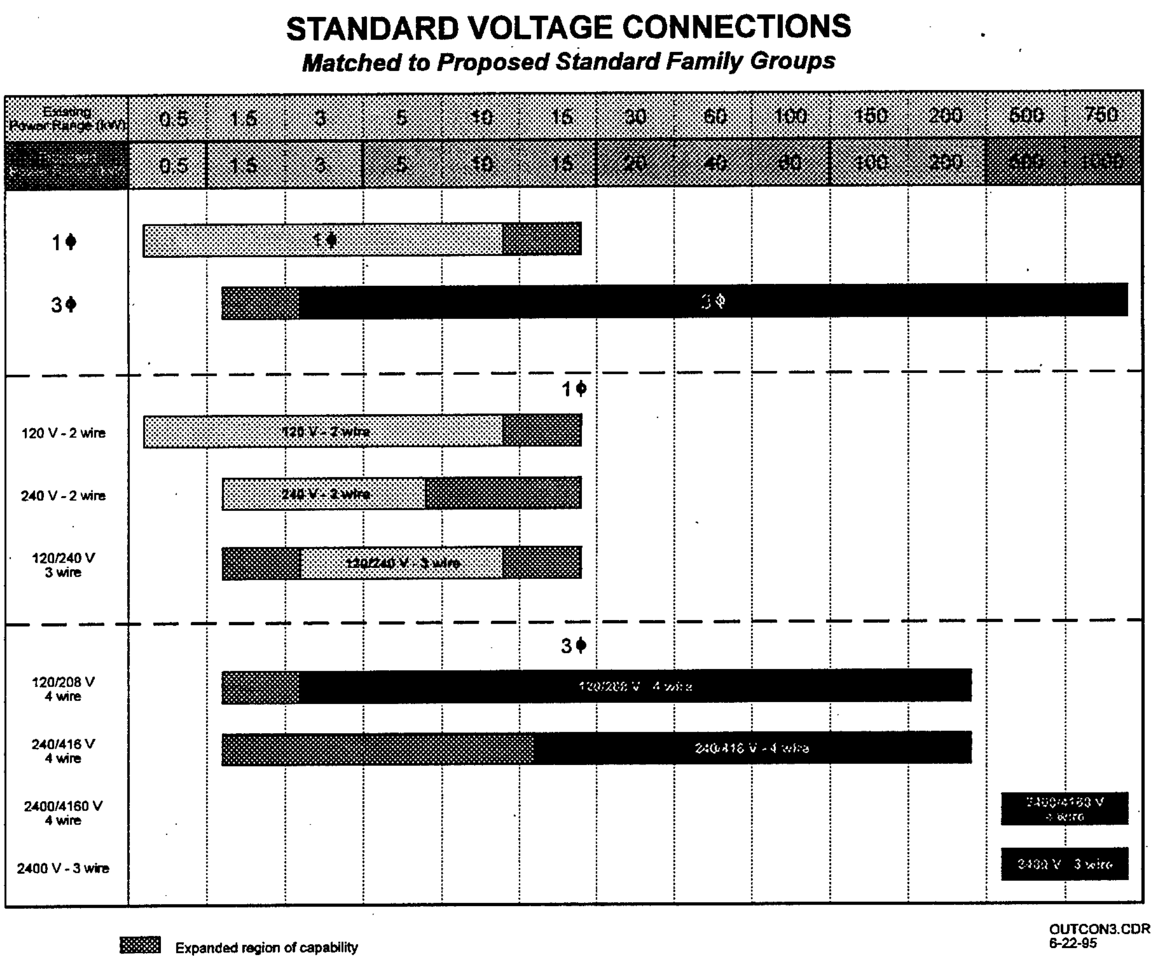


Figure 4. Optimized Reconnection Capability for Modular Approach

It is important to note that when considering PFC operation in both a 1ϕ and a 3ϕ configuration, the internal filtering must be sized accordingly. The 1ϕ configuration presents the high load ripple to the PFC, and thus must be considered when sizing the PFC internal DC link filter.

4.2.2. ARCHITECTURE COMPARISONS

Numerous architectures are available for implementing the HFA-PFC System. The more applicable ones include:

1. HFA-PFC - Single Function
2. HFA-PFC / Starter-Generator
3. Modular System Architecture
4. Power Management
5. Uninterruptible Power Source
6. Noninterruptible Power Source
7. Power Conditioning
8. HFA-PFC Independent Regulation
9. HFA-PFC Coordinated Regulation
10. Remote Power Generation / Localized Power Conversion

General comparisons of these approaches and tabulations of advantages and disadvantages of each are compiled in Table 7. Detailed descriptions along with functional block diagrams of each are in the next section 4.2.3.

One technology that is applicable across the various architectures is operation in the variable speed constant frequency mode. This alternative is discussed in detail under section 4.5.3 for Engine Interface Considerations.

The control of engine output power must be closely linked with the PFC output capability. A leading control technique must be used to anticipate HFA-PFC System load. The engine must be able to supply sufficient power in a short response time otherwise the PFC will try to compensate by increasing current. This momentarily raises stress on the power semiconductors while the engine output power increases. As the engine comes up to speed, the semiconductor current will drop respective of the HFA output voltage. This area is a balance among load transient response, HFA excitation capability, and PFC output regulation capability.

Table 7. HFA-PFC System Architecture Trade-Off Table

HFA-PFC SYSTEM ARCHITECTURE	PROs	CONs	COMMENTs
1. HFA-PFC Single Function	– Simple approach – Highest power density	– Limited use of technology capability – Unique design for each power range, high cost	
2. HFA-PFC / Starter-Generator	– Prewired for UPS operation – Provides multiple function capability (higher utilization of GEN SET components) – Eliminates existing engine starter component – Provides battery charge function	– Slight weight increase associated with preconditioning converter	– S/G technology can be used as option in other architectures
3. Modular System Architecture	– Tailor HFA-PFC configuration & construct unique output to meet specific system requirements – Soft fault modes – Accommodate engine power upgrades using existing HFA-PFC hardware – Base module designs may be used in additional applications (discrete power conditioning)	– Slight loss of packaging economy	– May have S/G mode for each power range – Can offer hot module replacement
4. Power Management	– Provide automatic output configuration using SSRs / mechanical relays	– Cost increase – Size increase	– Can apply to all architectures
5. Uninterruptible Power Source (UPS)	– Hot backup	– Time limited brownout coverage – Needs reconditioning stage or preregulated stage	– Can apply to all architectures with battery backup source available
6. Noninterruptible Power Source (NPS)	– Non-time limited	– Additional circuitry required for external fault isolation – Coordination with external sources	– Can apply to all architectures

7. External Power Conditioning	– Provide high quality 60 Hz output from alternate external input power source – Optional preconditioning front end module offers stand alone PFC power conditioning – Can use EP as primary power source with engine as backup source	– Additional cost	– Can apply to all architectures – Can be configured as an optional module
8. HFA-PFC Independent Regulation	– Fast load transient response	– Two major regulation loops, complicates stability, particularly with VSCF	– This approach is required if different output voltages are mixed, i.e. AC and DC from one MEPS
9. HFA-PFC Coordinated Regulation	– Simplified control scheme	– HFA-PFC System load transient response limited to HFA time constants	
10. Remote power generation / localized power conversion	– Suitable for power distribution applications – High voltage generation & distribution – Localized power conversion / step down	– Loss of PFC shared cooling system w/ gen & eng – Must be concerned with power quality between HFA/PFC from EMC respect	– Can use with most architectures presented

4.2.3. BLOCK DIAGRAMS

Block diagrams of various system architectures were created to assist in evaluating their applicability. A comprehensive set of block diagrams is presented in Appendix B. These correspond to the following brief descriptions of each system architecture. The block diagrams were created generically so they are independent of the power ranges for initial considerations. For this reason, inputs, outputs, and internal power busses are represented by one-line techniques. The architecture system number corresponds to the numbers used in the evaluation matrices. The conventions is "**SYS - #** ". The HFA or the PFC technology represented in each of the descriptions may be based upon the alternatives presented in the following HFA and PFC sections of this report. The block diagrams represent the power flow, logic and control signals are omitted for simplicity unless otherwise noted.

Since there are many perturbations possible of some features, only basic architectures are presented and discussed. Many features may be combined to produce multifunction capability. Functions that provide economies of scale are independently discussed. Functions that may be appended to various base architectures are described with respect to only one architecture, but they may be applied to other architectures. For example, the power management function is shown applied to the HFA-PFC Single Function (SYS-1) architecture, but it may also apply to a Modular System Architecture (SYS-3).

SYS-1 HFA-PFC Single Function

This architecture is the most fundamental for HFA-PFC applications. Its single function capability uses an HFA driven directly from an engine to generate electrical power. This power is supplied as an input to the PFC, where it is conditioned and regulated for output to utilization equipment.

SYS-2 HFA-PFC / Starter-Generator

This architecture builds on the previous SYS-1 architecture by adding the engine starter function to the HFA-PFC system. The purpose of this alternative is to eliminate the existing engine starter motors on the engine generator sets, thus reducing net weight.

The impact to the HFA and PFC depends upon the specific technology used for each. For instance, using a switched reluctance machine as a generator provides intrinsic operation as a motor due to the method of machine excitation. However, using a synchronous wound rotor or a permanent magnet machine requires contactors to control power flow either into, or out of the rotating machine. This configuration is represented in SYS-2a.

A battery input to the PFC is required, similar to the battery input to a traditional DC starter. Once this input is available, the UPS function becomes intrinsic to the architecture, and only requires a control algorithm change.

SYS-3 Modular System Architecture

A modular concept was developed to support field configurability, reduce logistical support, and reduce costs. The general concept is to develop a base unit design for both the HFA and PFC that forms the foundation for a group of power levels in the standard family of power ranges. The base unit output will be parallelable to provide step increases in output power capability. A standard gearbox for each power grouping will allow the operation of paralleled HFAs dependent upon the engine size selected. Unused mounting pads on the gearbox will be capped off. PFCs are parallelable by a standard plug in rack for each power grouping. The plug in rack will maintain the flexible output connections for reconnection capability in the field. The parallel control of the PFCs will be integral to their operation as an extension of the output frequency control. All necessary interconnects will be made through the plug in rack.

Architecture SYS-3a represents a variation of the base SYS-3, where independent outputs are available from a three unit parallel configuration. Each output may be independently regulated and controlled, each having a different output power type. Depending upon the HFA-PFC internal architecture, each HFA output may be independently controlled and distributed to a respective PFC. If PM based HFA machines are used, a common internal bus would be created, with each PFC providing output regulation.

SYS-4 Power Management

The power management function takes a basic HFA-PFC System architecture and appends an output power control stage. This feature can be used to provide load shedding in the event of system degradation. Another feature would be used to control load scheduling in a smart power management approach. Utilization loads could be manually scheduled for automatic energization and de-energization in order to limit maximum loading. Optionally, an intelligent controller may be used to provide automated load scheduling based upon data collected during normal operation. Load scheduling may be used to level utilization loads throughout an interval of time so that smaller power sources may be used. Non-critical loads may be operated during off-peak load periods.

Additionally, this feature can provide source bus integrity by removing faulted utilization loads. A system architecture that supports hot module replacement may benefit by automatically shedding loads to operate within the system rating while undergoing repairs. Mission critical utilization loads can remain on-line.

SYS-5 Uninterruptible Power Source

This architecture represents the classic uninterruptible power supply. A hot battery back-up is available as a time limited power source input to the PFC. The duration is determined mainly by battery size, utilization load, and PFC efficiency. A typical scenario may include a 40 A-hr battery operating at 5 kW load. The UPS would provide approximately 12 minutes of backup power from a fully charged battery. This time would be sufficient to properly shut down intelligent systems having volatile data and thus protect information, potentially remedy the primary power source outage, or switch to an alternate power source. The UPS approach could be coupled with a power management approach to shed noncritical loads during a primary power source loss in order to extend the operating time.

The depicted UPS architecture shows a common current electric DC starter using a battery. The battery power is also made available as an input to the PFC. In other words, with an electric start based engine generator set, the battery is already available and integrated with the intrinsic power conversion ability of the PFC. Naturally, the UPS feature is directly applicable to starter generator architectures.

Architecture SYS-2 shows the UPS approach for a starter generator application. There is effectively no architecture change required to implement this approach.

SYS-6 Noninterruptible Power Source

The noninterruptible power source approach has the ability to parallel power generation sources (HFA-PFC outputs) together. This technique provides an on-line, noninterruptible, non-time limited power generation source. The outputs of each MEPS may be interconnected through an arrangement of contactors as shown in the block diagram. This approach limits the maximum number of paralleled MEPS by the power rating of the contactors. Interconnect harnesses are required to synchronize the paralleled sources and identify a master MEPS, with the remaining paralleled units acting as slaves.

Alternately, each MEPS may have an output contactor for connection to a common bus. This approach could use a first on-line designation as master. The remaining MEPS would synchronize as they came on-line. In the event of a master failure, the slave would recognize the fault condition through harmonics on the line and return to internal control. The faulted unit will de-excite sensing an out of limit operating condition.

SYS-7 External Power Conditioning

This alternative architecture provides a power conditioning function for an external power source. The power conditioning function is intrinsic to the PFC design since the output power conditioning circuits and components are already present. In effect, the PFC is an external power conditioner. The feature can be used to condition power to a high quality 120 V - 60 Hz output from sources such as the 50 Hz European electrical grid. Primary power source may be the external power, with the engine and HFA as a backup power source. A battery backup for UPS operation would provide a hot uninterruptible power source while the engine is started and the HFA is brought up to operating speed. The battery backup is not depicted in the block diagram for SYS-7, please refer to SYS-5.

In order to effect this option, an independently regulated PFC that can accommodate a variety of input voltages typically encountered throughout the world is required. Optionally, a preconditioning unit may be used.

Incorporation of this function within the PFC, or as an optional module, can make the PFC a stand alone power conditioner. When integrated with a battery, it may also provide a UPS function. .Alternately, an independent front end converter may be configured to precondition the external power to the required input to the PFC. This independent front end may also become an option on the MEPS to provide the power conditioning function when the hardware is installed. Normal operation for this power conditioning configuration would be without the engine operating. The engine may become a backup power source in the event of a primary power source, that is a foreign utility grid outage. The battery backup would energize the UPS function to provide uninterruptible power while the engine is brought up to operating speed.

SYS-8 HFA-PFC Independent Regulation

The system architecture is shown to represent various system control techniques. The independent regulation scheme has separate regulators for the HFA and the PFC. Also shown is an integrated engine speed control which may be used to regulate engine power output and speed.

SYS-9 HFA-PFC Coordinated Regulation

The coordinated regulation architecture uses one regulation loop to control output voltage levels. Also shown is the engine speed bias signal to optimize engine operating point based upon utilization loads. If a PMG machine is used with coordinated regulation schemes, the speed bias signal would be the avenue of output voltage regulation.

SYS-10 Remote Power Generation / Localized Power Conversion

The last prominent HFA-PFC architecture presented is a remote power generation and local power conversion system. This architecture can generate electrical power for distribution to one or more remotely located power conversion units.

4.3. PFC TOPOLOGY OPTIMIZATION

Power Frequency Converter (PFC) technology has experienced significant strides in operating power levels and power densities as a result of major advances in power semiconductor technology over the last 10 years. The cost effectiveness has also been improved due to demand by high volume consumers such as the automotive industry. These factors translate into cost effective opportunities to reduce weight and size of tactical mobile electric power generating sets.

A block diagram shown in Figure 5, depicts the internal power conversion functions required to provide an integrated operation with the HFA and support additional system features. The input bridge provides the internal power bus. The battery input is for use with the electric start function and uses a flyback converter to interface with the DC link. This also provides the path for uninterruptible power supply operation in the event of loss of engine or generator operation. The $3\phi/1\phi$ inverter provides the 60 Hz AC output. An optional preconditioning module is shown that can be used to provide the power conditioning function when abnormal external power is available (e.g. 50 Hz). This module is based on a nondistorting input power factor design, presenting a unity power factor load to the external power source.

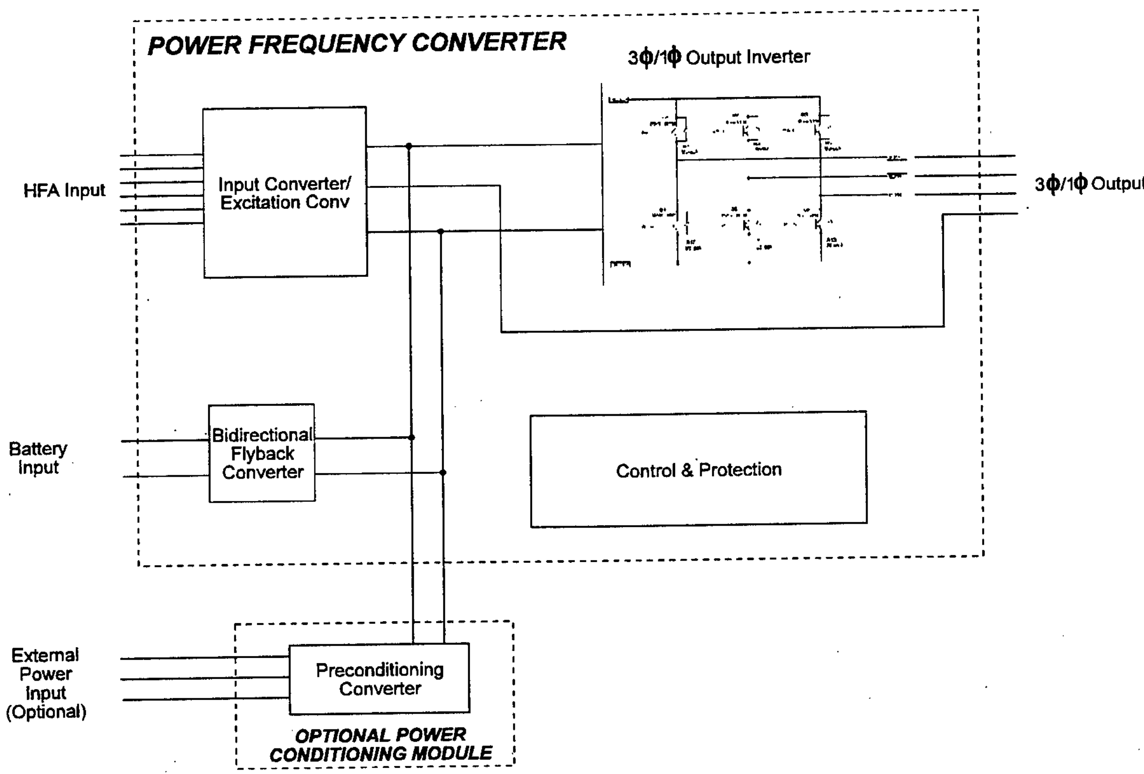


Figure 5. Power Frequency Converter Block Diagram

Table 8 summarizes the specific PFC topologies for corresponding power categories in the standard set of tactical mobile power sets as defined in the modular configuration. The topologies are capable of operating in parallel to support the modular system concept identified in the HFA-PFC System section. Supporting information on the selection of the topologies can be found in the succeeding subsections.

The features are PFC functions in addition to the basic converter function, of producing a high quality 60 Hz output power. Some of these features are iterative from the HFA-PFC System evaluation. They are included here since they will affect the PFC topology. UPS refers to an uninterruptible power source, more commonly known as a battery backup to the input power. The NPS refers to noninterruptible power source that effects paralleling capability of multiple MEPSs. Electric start is used in conjunction with the HFA to replace the existing DC starter associated with the main engine. The basic foundation to many of these features is intrinsic to the design of the PFC, and it is only a control function to include the extra capability. The reconfigurable output capability assures reconnection of the output to satisfy the multiple output configurations defined in MIL-STD-1332. Power management features are recommended for operation in the high power category (500-1000 kW) due to the output voltage levels encountered. This provides automated load connection control when the PFC has power ready, and it can mitigate the risk of shock by working close to high voltages.

The weight estimates are for the base unit rating in each of the power categories. These categories are shown at the top of the table. The weights correspond to the respective cooling technique which has a significant impact on weight and size. Weight estimations at this point indicate an oil cooled PFC design is approximately 50% of an air cooled PFC design weight for a given architecture. It should be noted that the two significant contributions to increased PFC weight and size are air cooled systems and transformer coupled designs. It is also important to note that the output transformers operate at a higher fundamental frequency then to 60 Hz output due to the summing techniques as described later in the appropriate subsection on the Summing Converter. This allows a weight advantage over a 60 Hz design. The weight for the 5 kW base unit includes an allowance to operate in a 1ϕ configuration, since this requires more DC link filtering capacity.

Cooling is based upon the HFA-PFC System approach. Optimum operation of the HFAs is based upon oil cooled hardware. Once this oil management system has been established, it is simple to integrate the PFC into the oil loop. This approach will yield the lightest weight and smallest system.

Table 8. Optimum PFC Topologies for Application

	POWER RANGE					
	0.5 kW	***1.5 - 3.0 kW***	***5 - 15 kW***	***20 - 60 kW***	***100 - 200 kW***	***500 - 1000 kW***
TECHNOLOGY	Resonant DC Link	Resonant DC Link	PWM Inverter	PWM Inverter	Summing Converter	Summing Converter
FEATURES		– Reconfigurable output	– UPS – NPS – Electric start – Battery charge – Reconfigurable output	– UPS – NPS – Electric Start – Battery charge – Reconfigurable output	– UPS – NPS – Electric start – Battery charge – Transformer coupled – Reconfigurable output	– NPS – Power management – Transformer coupled – Reconfigurable output
WEIGHT, lbs (Base unit rating for modular category)	4	9	13	26	207	1040
COOLING	Air	Air	Oil	Oil	Oil	Oil

4.3.1. IDENTIFICATION OF ALTERNATIVE TOPOLOGIES

The growth of the power conversion industry has presented numerous alternative topologies for use in a PFC. This project identified likely candidates and reviewed the benefits and applicability of each. The PFC topologies reviewed include:

1. 3ϕ Resonant DC Link
2. 3ϕ Stepped Waveform/Summing Transformer
3. 3ϕ Pulse Width Modulated Inverter
4. 3ϕ High Frequency AC Link
5. Phase Controlled Converter
6. Half Bridge
7. Full Bridge
8. Push-Pull Inverter
9. Flyback

The topologies included both AC and DC outputs since some DC output capability is required. Additionally, 1ϕ and 3ϕ circuits were reviewed to support reconfiguration of system output.

In order to compare the options, matrices of advantages and disadvantages were compiled. This represents the collective descriptions of each approach. A set of functional block diagrams of each topology was generated as a reference for compiling characteristics and understanding the operating principles of each. The descriptions, where applicable are found a subsection after the matrices, and the respective diagrams are located in the appendix.

Many general considerations and alternate technologies apply to the topologies described above, in a similar fashion. Some of the relevant ones include:

- Grounding
- Reconfigurable Output Connections
- Battery Charge Function
- Modular Architecture
- Paralleling Capability
- Control & Protection
- Future Trends

Reconfigurable output connections for 1ϕ or 3ϕ operation is typically addressed by changing the output connections in the Modular System Tray in much the same way output reconnections of current generators are made. This step will also signal to the PFC the required output phase shift between the individual output phases. A 1ϕ requires no phase shift, a 3ϕ configuration requires 120° phase shift among phases. Special consideration must be given during the detailed design to assure load sharing among outputs when operating in 1ϕ mode. Converters that operate can operate in the two output configurations must have their internal DC link sized for ripple associated with the worst case 1ϕ operation. Different output voltages can be performed in the same manner, thus requiring a physical operation, reducing the possibility of misconnecting output voltages to inappropriate load ratings. The 3ϕ Summing Transformer Inverter architecture requires physically reconnecting output wiring configuration. The direct coupled inverter outputs, voltages changes may be performed by a selection switch. The 3ϕ Summing Transformer architecture is not reconfigurable to a 1ϕ operation, since extensive wiring modifications would be required to vectorily sum the phases.

Special attention must be given to the selection of output filter component selection in order to satisfy selectability of 120 or 240 VAC. The output filters must be capable of operating with the complementary V*I characteristics of the output rating.

A battery charge function may be supplied in several fashions. The most simplistic is to float the battery on a rectified step down output voltage of the HFA-PFC System output. Similar to many applications today. Alternately, the input converter used during electric start may be configured as a bidirectional converter to charge the battery under normal system operation. This approach is extremely attractive when using the battery to supply the UPS mode of operation in the HFA-PFC System. A fully charged battery will be assured for maximum backup time.

The modular configuration automatically defines the converters must be capable of operating in a parallel output arrangement. This is an advantage that allows the parallel operation of MEPS since the control algorithms are established, and the paralleling capability is inherent in the design. Or the inverse could be true, if parallel operation is a requirement (exists in current MEPS), then the function is inherently present to support the modular concept. The PFC frequency control is established by an internal reference. This may be varied to provide no break power transfers, where a second MEPS may paralleled and brought on-line without interruption of bus power. The frequency control can be used to slave to other units for modular operation, or parallel MEPS operation.

A detailed design process must address the control and protection requirements of the PFC and HFA-PFC System. These include logical operation, fault detection and response, and Built-In Test (BIT). Interface with the equipment operators must be addressed at the detailed design stage. Optional rheostat type control must be considered to allow the user to set the output voltages required depending upon distribution wire lengths. This may be provided as an optional remote point of regulation. The PFC uses a discrete sensing wire to regulate output based upon remote sensing. This scenario can default to output voltage regulation, if the wiring is not connected.

Future trends in power conversion will push operating envelopes of the resonant DC link architectures to higher powers as power handling capability of components continues to grow. This will result in their application in the higher power ranges with these developments. In concert, power densities will continue to improve. This will also be supported by further miniaturization of control circuits and increases in computational ability for controlling complex resonant architectures and motor control functions. Applications of fuzzy logic and neural network control algorithms may evolve that allow a system to "fine tune" output under varying load conditions.

4.3.2. Matrix of Topology Comparisons

The matrices presented in the following pages summarize the information on each topology. Table 9 show advantages and disadvantages of various 3ϕ topologies. The topologies are further defined in subsection 4.3.3 Topology Descriptions, and have corresponding block diagrams for reference in the appendix.

Table 10 applies to 1ϕ configurations. General topology considerations are given in Table 11. Approaches to DC output topologies are presented in Table 12.

Tables comparing key voltage and current operating characteristics for the inverter topologies and the power semiconductors is located in Appendix D. It should be noted that there are may possible variations on each of these topologies that may be used to refine the actual detailed design and optimize selection of a specific power semiconductor chip. These tables result from an analysis performed using an EXCEL spreadsheet. Three topologies are compared across all power ranges considered in this project.

The first table in Appendix D, on page D-2 compiles the actual operating output power levels in watts. The second table lists the system output voltages during the high voltage output connection based upon MIL-STD-1332. Page D-4 shows the output line currents in amperes corresponding to the high voltage output. The required internal DC link voltages are calculated on page D-5 based upon the architecture. The respective average DC link currents are shown in the lower table on D-5. The table on page D-6 reviews the DC link characteristics with a resonant link inverter application. Page D-7 shows the peak currents in the power transistors. Page D-8 has a table that summarizes the same information for the low voltage output configuration. The summing transformer approach uses connections on the secondary to reconfigure its output. The internal DC link voltage remains the same, as does the peak transistor currents, for the corresponding output power levels at the high voltage output configuration.

It should be noted that these calculations are intended to provide rough order of magnitude comparisons at the preliminary design stage. They exclude certain factors such as efficiency and magnetic component excitation currents. They may be considered reasonable to within 10%.

The tables used for the high output voltage configuration basically establishes the voltage ratings of the power semiconductors. The tables corresponding to the low voltage output establish the current handling requirements of the power semiconductors.

Table 9. 3ϕ PFC Topology Trade-Off Table

3ϕ - AC PFC TOPOLOGY	*PRO*	*CON*	*COMMENT*
1. 3ϕ Resonant DC Link Inverter	– Easily reconfigured for 3ϕ/1ϕ output – High efficiency – Low EMI – Low heat rejection/signatures – High frequency operation / small output filter – Low switching losses	– New technology (unproved) – Low power level applications due to resonant currents being much greater then load currents – Voltage limitations (output & DC Link) – High component stress with high power – High distortion with high power factor loads requiring large output filtering – Complex control over wide load variation	– Soft switching technology, ZVS, ZCS
2. 3ϕ Stepped Waveform / Summing Transformer Inverter (Square wave, Harmonic Neutralization Inverter)	– Proven technology – Intrinsic expandability for high power ranges, Parallelable bridges for increased power – High voltage/power output capability – Transformer isolated output – No output DC content possible – Provides assorted voltage connection taps off XFMR – Lower peak currents in power device then resonant or PWM inverter	– Low frequency XFMR, function of # of stages and fundamental output freq – Higher weight – No single phase configuration option	– 2 to 6 output bridges (or more, multiple and in phase parallel output bridges) – Wye & Delta combinations reduce output filter requirements – May be used down to 20 kW based upon MIL-STD -1332 output configurations
3. 3ϕ PWM Inverter a) Modulated carrier b) Optimum response (bang-bang) c) Programmed Waveform	– Easily reconfigured for 3ϕ/1ϕ output – Individual phase regulation – Proven Technology – High frequency operation / small magnetics & output filter – Quality output waveform with *pf*	– Limited power handling by semiconductors – High switching losses – Output voltage limitations	–
4. 3ϕ High Frequency Link (AC link inverter)	– Eliminate input rectifier bridge – Eliminate/reduce output bridge switching losses – Low EMI	– Complex AC inverter switches, use 4 diodes & trans, 2 trans. & 2 diodes, or 2 SCRs – New technology – High distortion with high power factor loads requiring large output filtering – Complex reactive current handling during poor power factor operation – No single phase configuration option	– Essentially moves input rectifiers to inverter switches. – Topology is very similar (based upon) cycloconverter approach, using ZVS – Can configure 3 separate paths for 3ϕ input / 3ϕ output – May require resonant filtering
5. Phase Controlled Converter (3ϕ Cycloconverter)	– Ideal for paralleling – Eliminate input rectifier bridge – High power output capability using natural commutation SCR bridges, when connected to existing AC bus	– Complex commutation circuits if not connected to energized AC grid system – High distortion output requiring large output filtering, phase controlled regulation – No single phase configuration option	– SCR based technology

Table 10. 1ϕ PFC Topology Trade-Off Table

1ϕ - PFC TOPOLOGY	PRO	CON	COMMENT
6. Half Bridge	– Can use in 3ϕ configuration	–	–
7. Full Bridge	– Peak device current is 1/2 of half bridge	– High component count when configured for 3ϕ operation	–
8. Push-Pull Inverter (XFMR Coupled)	– Can use in 3ϕ configuration – Isolation thru XFMR intrinsic to design – Common ground for power devices – Good for low voltage sources	– Heavier weight associated with output XFMR – DC content on XFMR primary causes saturation –	–
9. Resonant DC Link	– Can use in 3ϕ configuration	– New technology (unproved) – Low power level applications due to resonant currents being much greater then load currents – Voltage limitations (output & DC Link) – High component stress with high power	–
10. High Frequency Link	– Can use in 3ϕ configuration	– Complex AC inverter switches, use 4 diodes & trans, 2 trans. & 2 diodes, or 2 SCRs – New technology	–

Table 11. General PFC Topology Trade-Offs

GENERAL PFC TOPOLOGY	PRO	CON	COMMENT
11. Transformer Coupled Output	– XFMR output emulates typical generator output connection capability – Provides full range of output connection capability – No DC component possible in output – Provides "effective" paralleling of output stages to increase total output power capability	– Weight increase	– Can use XFMR leakage inductance as an integral part of output filtering – XFMR may be designed for pulse frequency using certain architectures, thus reducing size – Can use this approach with most topologies
12. Direct Converter Output	– Light weight	– Needs discrete output inductor for output filtering – Limited output connection capability, will impose constraints – Needs addition of NFT to cover all output connections of MIL-STD-1332 or overrated components (V*I characteristics) – Potential minimal DC component in output – Potential large DC component in output during inverter failure modes	– Can use this approach with most topologies
13. Modular Architecture	– Expandability – Configurability – Improved logistic support – Lower cost – Common components – Paralleling capability provided by modular design intrinsically allows MEPS paralleling operation	– Small redundancy in packaging (weight)	– Use back plane type rack plug in connectors – This can apply to most all PFC Topologies being reviewed.
14. Unique Architectures for Individual Power Ranges	– Maximum size and weight optimization for each power range	– Expensive development approach – Expensive production costs – High Life Cycle Cost – High logistical support requirement	–

Table 12. DC PFC Topology Trade-Offs

DC PFC TOPOLOGY	PRO	CON	COMMENT
15. Flyback	– Energy transfer base operation, ideal for operating in paralleled configuration	–	–
16. Full Bridge	– Low device stress	– High component count	–
17. Resonant DC Converter	– High efficiency – Soft switching (low stress)	– Complex design	– The attributes are similar to those of an AC application

4.3.3. TOPOLOGY DESCRIPTIONS

Functional block diagrams corresponding to each of the following topology descriptions are located in Appendix C. The block diagrams detail the major elements of each approach and show their basic power interconnections. The following descriptions present general concepts, and significant characteristics about each approach where applicable. Some alternatives require little or no explanation. The descriptions are targeted at presenting characteristics related to the selection of optimum configurations for use in a HFA-PFC system. Detailed schematics and operating descriptions are not the objective of this task, but may be found in technical journals and modern textbooks on power conversion.

Most of these topologies have been available for quite a period of time. The increase in power handling capability of semiconductors brings certain topologies into favor periodically. Additionally, high speed digital control techniques help to provide improvement in the designs that make them effective to use.

<u>3ϕ - PFC Topology</u>

The following topologies are well suited to application in 3ϕ converters. Many of the 3ϕ options are built around the basic 3ϕ inverter bridge. This is illustrated in Figure 6 for reference. This schematic is used for all "3ϕ OUTPUT BRIDGE"s shown in the block diagram.

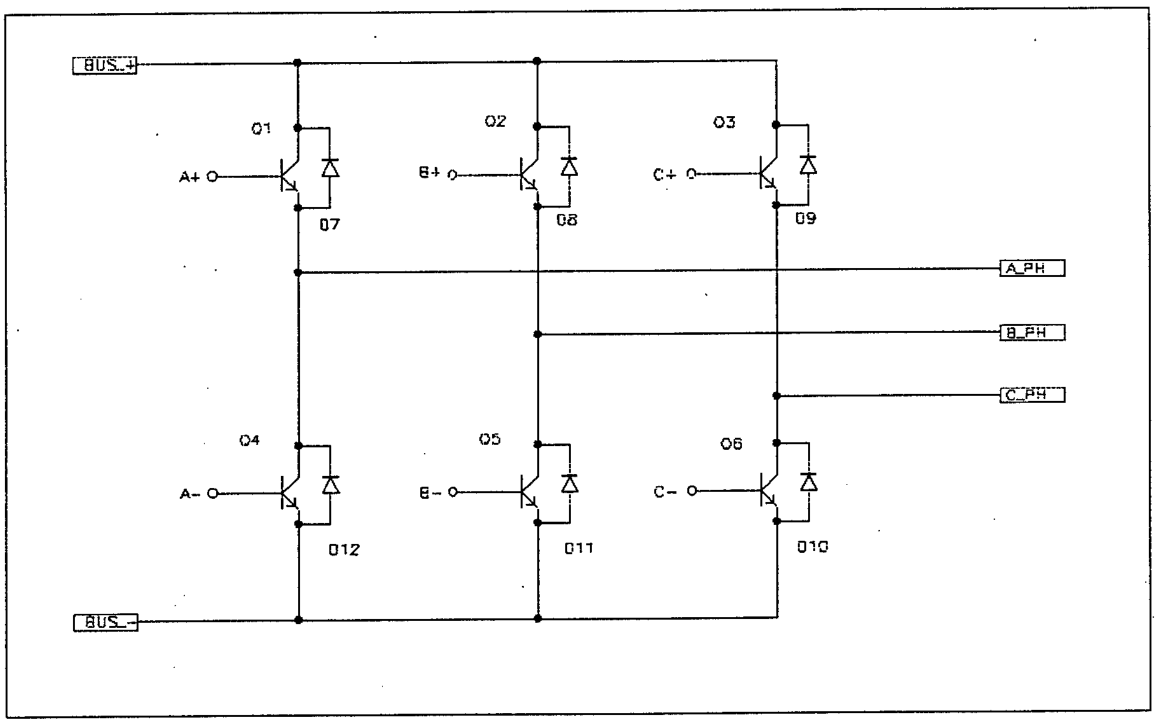


Figure 6. Fundamental Three Phase Inverter Bridge

PFC-1 3ϕ Resonant DC Link

Many recent variations of this known topology are now surfacing with the renewed interest due to the high power capability of semiconductors.

The primary advantage of this topology is that it provides soft switching of the power transistors. Which reduces switching losses in the power semiconductors. This provides two principal benefits. Overall converter losses are reduced and the switching transistors experience lower switching stresses. The later assures operation well within the Safe Operating Area (SOA) of the power transistors. An additional benefit is reduced EMI due to switching characteristics having a quasi-sinusoidal edge instead of the hard switching square wave. One caveat is that additional losses are introduced in the resonant circuit that must be weighed against the reduced switching losses.

The principle of operation is to create a resonating voltage on the DC link that ranges from zero to approximately twice the input voltage. Techniques are possible to recover some of the resonant energy and reduce the peak resonant voltage. This helps to reduce the sustaining voltage requirements of the components.

Complications with this technology include high currents in the resonant circuit. These must be much larger then the load current to maintain a resonating link voltage. All the resonant energy must flow through the resonant circuit, usually requiring particular attention to capacitor selection and application. This high current corresponds to new losses in the resonant circuit elements which can be comprised of inductors, capacitors, and semiconductors. The peak current through the output transistors increases to accommodate for the loss of current at the edges of the traditional square wave operation.

Output voltage regulation is achieved through a combination of varying the resonant link frequency to adjust the impedance of the resonant circuit, and selecting an appropriate pulse pattern in the output. Stability control over large load variations is difficult. This usually forces the operation into a quasi-resonant mode of operation. The benefits of resonant operation are now realized depending upon load. Mitigating DC content in the resonant converter output puts another control loop into the complex regulation scheme.

High resonant link frequencies aid in reducing resonant circuit components, but there is a practical limitation. As frequency increases, inductor designs get more complex, and skin effect begins to play a large factor in magnetic design. The power semiconductors have realistic switching limits. MCT's are capable of approximately 20 kHz, and IGBT's can operate up to 40 kHz.

The resonant DC link requires a Neutral Forming Transformer (NFT) when operated in conjunction with an HFA that has no neutral connection such as a variable reluctance machine. This is necessary in order to provide a neutral reference, and grounding protection of equipment and personnel.

Due to their additional circuitry and control complexity, Resonant link converters usually become advantageous when the circuit design stresses exceed the capability of available power semiconductors.

PFC-2 3ϕ Stepped Waveform / Summing Transformer Inverter

The summing transformer inverter is based around the standard 3ϕ Output Bridge. Each output bridge is effectively a 3ϕ inverter. Using a transformer to sum the outputs of multiple bridges can raise the output power rating of a PFC to very high levels. The output of the individual bridges are phase shifted in order to reduce output harmonics. This technique works on the principal of a more traditionally known harmonic neutralization converter, which used single leg bridge outputs - phase shifted to minimize harmonic content. The harmonic neutralization converter should not be confused with the harmonic elimination, which is a switching control algorithm used in a 3ϕ bridge to eliminate specified harmonics from the output.

The main advantage of this approach is that is allows the output bridges to be ***effectively*** paralleled without actually paralleling discrete power semiconductors. Appendix D, PFC-2 shows a 6 bridge configuration, producing a 36 step output waveform. These steps are then filtered using an output filter. Output load is equally shared among the bridges provided that the summing transformer is balanced and the turns ratios are equal.

Output voltage regulation is performed by closed loop control of the HFA output. The inverter output bridges operate in a fixed conduction duty cycle. Frequency is set by a precise internal timing reference oscillator.

The major drawback to this technique is the weight of the output transformer. One aspect of the transformer design that may be used to reduce weight is that the effective operating frequency is equal to the output frequency multiplied by the number of steps in the output waveform. This results from the steps being applied to the transformer appearing as pulses. The transformer operates as a pulse transformer. The operating frequency is much higher then the 60 Hz, and the resulting transformer may be much smaller.

The use of the output transformer provides an electrically isolated inverter output with a neutral that may easily be referenced to the common ground structure. This converter is not configurable as a 1ϕ output due to the summing techniques of the transformer primary.

No DC content is possible in the PFC output with this configuration.

PFC-3 3ϕ Pulse Width Modulated Inverter

The Pulse Width Modulated (PWM) inverter is an extension of the 3ϕ output bridge. It is a commonly applied and well known topology. This configuration is used to provide a direct bridge output to an output filter. One basic mode of operation is to control switching of the power transistors to synthesize a sinusoidal output after filtering.

Output regulation is performed by a dedicated voltage regulator that may compare a sample of the output waveform to a reference voltage, thus generating an error signal for PWM control. Several approaches are possible including: modulated carrier, optimum response (bang-bang), and programmed waveform. Precise voltage and frequency regulation is possible. Switching of output voltage levels from 120 to 240 VAC may be performed by the PWM technique. 1ϕ or 3ϕ operation is determined by the dwell between phases and the output connection. Compensation to mitigate output DC content is required.

System neutrals and grounding are easily defined with this architecture. A capacitor divider network may be used across the internal DC link to establish a ground reference for the converter output. The technique is also compatible with the VRM design.

PFC-4 3ϕ High Frequency Link (AC Inverter)

The high frequency link AC inverter uses the basic 3ϕ output bridge, but replaces each power switch with a bidirectional switch. The link voltage is a high frequency AC voltage. Control algorithms establish a power switching sequence that passes positive portion integral half cycles of the AC link voltage to the output. The pattern synthesizes an AC output by "gating" the AC link half cycles to emulate a low frequency AC output. An integral number of half-cycles are used to avoid any DC content in the output.

Each bidirectional switch must be composed of one transistor and four diodes, or two transistors and two diodes. The overall converter has the same quantity of power semiconductors, with essentially the same rating as the conventional input bridge / output bridge arrangement.

Potential advantages of this approach are elimination of switching losses since the power switches are switched at the zero crossings of the AC bus.

A resonant AC link circuit is required to operate at the input frequency.

Control algorithm's are very complex for this approach and require high speed computational capability. Additionally, control during low power factor is difficult.

PFC-5 Phase Controlled Converter (Cycloconverter)

Is the classic thyristor based AC to AC converter.

1ϕ - PFC Topology

The following topologies are well suited to 1ϕ converters. They were reviewed to assess their application for the one phase generator set output requirements. Consideration was given to reconnecting them to also support the 1ϕ / 3ϕ reconnection criteria specified in MIL-STD-1332. Most of these topologies can be applied in triplicate with a 120° phase shift in the frequency control to provide a 3ϕ configuration.

PFC-6 Half Bridge

The half bridge effectively operates as one bridge leg output of the 3ϕ PWM inverter. An additional requirement is a neutral forming capacitor connection. The 3ϕ PWM inverter has the intrinsic ability to operate with the three outputs paralleled as a 1ϕ inverter.

PFC-7 Full Bridge

This architecture has a high component count when used as in a three phase bridge configuration. Requires an isolation transformer to ground one side of the output, or for use with a load that has one side grounded.

PFC-8 Push-Pull Inverter (XFMR Coupled)

The push-pull inverter design requires an output transformer. The magnetic design may be based upon the fundamental operating frequency of the inverter, thus reducing its size.

PFC-9 Resonant DC Link

The 1ϕ resonant DC link inverter operates in a similar fashion as the 3ϕ configuration.

PFC-10 High Frequency Link

The 1ϕ High Frequency AC link inverter operates in a similar fashion as the 3ϕ configuration.

General PFC Topology

The following variations may apply to most all of the topologies considered to this point.

PFC-11 Transformer Coupled Output

If an output transformer is operated at the fundamental 60 Hz line frequency, its size will be very large and preclude its application due to loss of weight advantages. This option is only feasible where higher fundamental frequencies are possible.

The output filter associated with this architecture is usually smaller then that required by the direct converter output since a portion of the filtering may be derived from the leakage inductance of the transformer.

PFC-12 Direct Converter Output

This approach uses an output filter in series with the 3ϕ output bridge. Like the previous example, the output filter magnetics must be operated at a high frequency commensurate with the inverter operation to maintain weight savings advantages for its applications.

PFC-13 Modular Architecture

The Modular Architecture approach requires that frequency and phase information pertaining to the output voltage be communicated to the complementary modules. This may be accomplished through a discrete interconnect or through interconnects in the mounting rack.

PFC-14 Unique Architectures for Individual Power Ranges

Each previous alternative may be applied in a unique design for each power range. The modular approach appears optimum, but is not required for the implementation of an HFA-PFC System. Unique designs could be created for the 20 kW, 40 kW, and 60 kW levels, for instance.

There is no corresponding block diagram for this alternative, as it is essentially each of the alternatives previously discussed.

4.3.4. COMPUTER MODELS AND SIMULATIONS

Computer simulations were performed on the 3ϕ Summing transformer architecture to demonstrate some circuit simulation capability during this project. A set of data was generated for 1 bridge, 2 bridge, 4 bridge, and 6 bridge configurations. Computer simulations take a large amount of time to effect a realistic model where data has significant meaning. The simulations were limited to the one approach during the Phase I effort. It would have be easy to spend all the project time focusing on the simulation of one architecture, let alone attempting to perform simulations on all the variations.

The simulations presented for this phase of the project do not represent optimized detailed designs. They are intended to demonstrate the circuit operation along with some of the idiosyncrasies of the architecture simulated. These simulations would be an integral part of a design undertaken to pursue development of the HFA-PFC System.

Simulation results are located in Appendix E. The schematic for the 6 bridge Summing Converter is shown in the first section. The bridge configuration in this schematic is identical to 4, 2, and 1 bridge simulations. Simulations were also performed on converter circuits with and without an output filter to show the reduction in harmonic content as the number of steps increases, and the corresponding reduction in output filtering requirements.

The second section in Appendix E show the simulation results of a 6 bridge summing converter architecture with an output harmonic filter. The output power rating is 100 kW. The first set of data shows the harmonic decomposition of the output waveform. The plots that follow are titled, and represent a harmonic spectrum of the output voltages, line-to-neutral output voltages, line-to-line output voltages, expanded plots of output voltages, and line currents.

The next section shows the same information for the same converter configuration at approximately no load.

The following section simulates the identical 6 bridge configuration, but without an output filter. The output power level is 100 kW. The respective data is included in this section. The waveform smoothing apparent in the output voltage plots is due to the simulated leakage inductance of the output transformer. As will be seen with the next set of plots, this smoothing is load dependent since the leakage inductance is effectively in series with the output connections.

The next section simulates the same "filterless" circuit at approximately no load. The discrete summation of the square wave mode output bridges may be seen in the stepped appearance of the output waveforms. Although, this output appears very jagged, its actual total harmonic distortion is approximately 4.8%. The leakage inductance filtering effect has a decreasing affect on the output waveform as the load current decreases. From these simulations, it may be seen that a small amount of output filtering is required.

The last section in Appendix E shows the output voltage waveform for the different bridge configurations of the summing converter.

An important result of the simulations is an analysis of the output harmonic content for various summing converter configurations. Table 13 summarizes the results for a 6 bridge configuration with and without an output filter for various loads. This information was derived from the tabular PSPICE output where a Fourier analysis is performed on a particular node.

Table 13. Six - Bridge Converter Output THD

	Percent Total Harmonic Distortion (%THD)	
Output Power	Unfiltered Output	Filtered Output
173 kW	1.05	1.07
100 kW	1.45	1.40
86 kW	1.68	1.488
58 kW	2.11	1.73
35 kW	2.75	2.01
17.3 kW	3.78	2.26
8.6 kW	4.47	2.47
approx 0 kW	4.80	2.92

A comparison %THD of the different bridge configurations is shown in Table 14.

Table 14. No Load Output %THD for Various Output Bridge Configurations

Output Bridge Configuration	Unfilter Output (%THD)
6 Bridge	4.80
4 Bridge	7.23
2 Bridge	14.64
1 Bridge	30.55

As can be seen, the above simulations are quite involved, and consume a large amount of project time. Simulations of all possible configurations would have been impractical at this point of conceptual design and preliminary design stages. The simulations are required during a detailed design phase in order to optimize the detailed circuit designs, and assist in validating design and operation. Simulations will also prove invaluable during prototype fabrication and test.

4.4. HFA APPROACH OPTIMIZATION

A review of High Frequency Alternator (HFA) technology was undertaken using criteria and evaluation techniques similar to those used in the aerospace industry. Primary considerations for evaluating weight reductions in generator technology are the speed range and the corresponding applicable machine design. The net result of this effort shows a significant opportunity to provide substantial weight and size reductions with respect to the generator. The results of this work task are summarized in the Table 15.

The table shows the preferred machine technology applicable to a corresponding power range. The power ranges support the modular concept for the standard family of generator sets established earlier. They are identical to the power ranges used under the PFC section. It is important to note that the power range values reflect the power level at the output of the engine generator set. The actual power output of the HFA is slightly higher by the amount equivalent to the PFC losses. For instance the HFA required for the 20 kW system will have an output of approximately 21.7 kW.

A major generator weight reduction is possible through operation at higher speeds. The candidate speed ranges of generator operation are well within the operating capabilities of their respective technology. Mechanical designs are valid in these speed ranges, as many turbines engines use rotors with similar and larger moments of interia, and support bearings, to handle the loading and speeds seen by the HFA.

The HFA weights are based upon the modular HFA-PFC design concept. The weights given in the table correspond to the basic module HFA for the respective power range. For instance, the 20 - 60 kW range weight is for the 20 kW machine that may be configured in parallel, as described under the HFA-PFC section, to yield 40 or 60 kW output. These weights are considered conservative in the aerospace industry, especially when considering the operating speeds. Recent technology trends provide power densities as high as 0.416 lb/kVA for oil cooled machines. Air cooled machines have also experienced increased power density to 1.07 lb/kVA from levels of 2.5 kVA in the 1950's.

Air cooling techniques were selected for HFAs in the range from 0.5 to 3.0 kW based upon their simplistic design. Air cooling yields a slightly larger design and lower power density. Compared to the current systems, a significant improvement is realizable. Oil cooled HFAs are used in the higher power ranges in order to yield significant weight savings over air cooled machines.

Significant HFA options are shown that have the potential to contribute to additional weight savings when considering the entire system. This primarily involves using the HFA as an electric starter for engine start function. The Switched Reluctance Machine (SRM) technology almost provides this operation as an intrinsic function to the design. The SRM excitation technique is identical in both generator mode and motor mode. The prime difference is where the excitation is applied relative to the angular position of the rotor.

Some of the technology applications will actually change in the future as others become more favorable. For example, one of the realistic limiting factors with variable reluctance technology applications is the power semiconductors used to excite the machine. As their power rating increases, they will be capable of supporting the VRM technology. At this point, the VRM technology will move into favor for the highest power application of 500 - 1000 kW.

Likewise, as the cost of permanent magnet material is reduced with increased use, the PM technology machine may move into the 5 - 15 kW range in order to take advantage of a reduced quantity of power semiconductors in the associated PFC.

Table 15. HFA Technology Application

	POWER RANGE				
	0.5 - 3.0 kW	***5 - 15 kW***	***20 - 60 kW***	***100 - 200 kW***	***500 - 1000 kW***
TECHNOLOGY	Permanent Magnet	Variable Reluctance	Variable Reluctance	Variable Reluctance	Brushless DC (wound rotor)
SPEED RANGE	15,000 - 30,000 rpm	22,000 - 44,000 rpm	22,000 - 44,000 rpm	12,000 - 24,000 rpm	9,000 - 18,000 rpm
Weight, lbs (Base Modular Unit for Power Range)	0.5 kW - 3 lbs 1.5 kW - 7 lbs	11	27	94	400
Cooling Technique	Air	Conduction Oil	Conduction Oil	Conduction Oil	Spray Oil
Options		Electric Engine Start	Electric Engine Start	Electric Engine Start	Electric Engine Start

4.4.1. IDENTIFICATION OF ALTERNATE TECHNOLOGIES

HFA alternate technologies include a variety of electric machine technologies, and a subset of technologies applicable across the variety of electric machines. The comprehensive set of machine technologies available for implementing HFA designs is to numerous to include in this report. Therefore, a sample of likely candidates was down selected for evaluation. These include:

> ***Permanent Magnet*** – A favorable technology known for compact size and light weight designs.
>
> ***Variable Reluctance*** – Well known technology that is seeing a renewed interest due to the increased capability of the power electronics needed for excitation and conversion.
>
> ***Wound Rotor Brushless DC*** – This is a traditional synchronous generator using a doubly fed configuration with rotor excitation coupled by electromagnetic means.

These machine technologies are explained in further detail later in this section. Unique characteristics of each machine are discussed, as well as special considerations for application of each technology where applicable.

The subset of technologies applicable to the machines being evaluated include:

- Operating speed
- Cooling techniques
- Generator pole configuration
- Output phase configuration
- Future trends

As previously described, the single largest factor attributing to weight reduction is the increased HFA operating speed. This is based upon the fact that magnetic material peak operating flux decreases as frequency increases for a given core size and power level. By increasing the operating speed, the HFA fundamental operating frequency is increased, and the weight can be reduced for the same output power rating. The weight relationship is inversely proportional to the operating frequency, neglecting core losses. Realistic upper limits are encountered when windage, core loss, and conductor skin effect at high frequencies associated with high speed is taken into account.

Typical 4 pole, 60 Hz generators operate at 1800 rpm. Present day 2 pole, 400 Hz aircraft generators operate at 24,000 rpm. The HFA-PFC concept allows even higher operating speeds since the output frequency is conditioned by the PFC. Operating speeds as high as 60,000 rpm are conceivable and inline with turbine engine machinery velocities. The operating speeds evaluated during this project (up to 44,000 rpm) are up to 24 times the current nominal speeds. Present APU turbine engines operate between 40,000 and 60,000 rpm having rotor masses similar to the HFA rotor masses being considered.

An alternative to increasing generator speed is to increase the pole count of the machine. Doubling or quadrupling the poles would theoretically reduce the generator magnetic material weight by half and a quarter, respectively. While these are reasonable weight reductions, they are not optimized. Increasing the number of poles beyond this is generally considered impractical from a physical layout perspective. Additionally, the PFC weight will be increased substantially to account for increased input filtering required for the lower input frequency.

As will be seen in the sections describing the individual machine technology, each has its own speed limiting factor. Special considerations must be given to the mechanical designs of these high speed machines. Upper speed limits on machines based on mechanical parameters include windage losses, mechanical integrity, and bearing ratings. Another important consideration for high speed operation is bearing technology and their lubrication techniques. Oil lubricated bearings operate well in the high speed ranges. Grease packed bearings are usually applicable to about 15,000 to 18,000 rpm maximum.

Machine cooling techniques are another common design aspect among the HFA types. Several fundamental approaches are available including air cooled, oil cooled, and liquid cooled. The simplest approach is usually air cooling, which is also the least efficient. Air cooling may be accomplished by impinging air flow directly through the center of the HFA. This technique has drawbacks when the system is operated in a hostile environment such as dust. Foreign matter can erode electrical insulation, cause particulate matter buildup, and eventually cause a dielectric breakdown. If the system is operated in a high humidity or wet environment, this will accelerate dielectric breakdowns by ingesting water. These difficulties may be averted by using a closed frame design with a convection cooling technique to draw heat from the machine internals and transfer it to the frame or case. Here it may be dissipated to the ambient through cooling fins which improve the heat transfer efficiency. The low thermal efficiencies associated with heat transfer in air require large surface areas for dissipating heat. This contributes to a larger machine design. Air cooling also presents a conflict with high speed operation and the use of traditional grease packed bearings in air cooled designs. Upper speed ranges are typically limited to about 18,000 rpm. Oil lubed bearings, with the added complexity of integrating an oil lubrication system and seals, must be used to extend the operating speeds. New ceramic bearing technology may be used to eliminate lubrication requirements in the future.

Forced air cooled machines must provide a source of cooling air. If a fan is designed as an integral component, consideration must be given to the machine operating speed. Fans rotating at high velocities produce high levels of high frequency noise. An alternative is to use an air pump operating from a low speed take-off from the engine to supply a high volume air flow. Natural convection cooling and cooling fins may be used to aid in removing losses from the stator and housing.

Oil cooling can provide additional weight savings by improving heat transfer characteristics, and allowing the cooling interfaces to be smaller. In some cases a 50% reduction in weight is possible over the equivalent air cooled machine. Cooling efficiency is improved by passing oil directly through the machine. This may be in passages around the stator, through the rotor, or interleaved with the stator windings. Oil cooled machines provide a closed design to the atmosphere, eliminating intrusion by foreign contaminants. Oil cooling can be performed by an individual system that is dedicated to the HFA with a heat exchanger to the atmosphere, or to the main engine radiator. Optionally, the HFA may have a shared oil system with the engine and gearbox. Oil cooling techniques provide a means for lubricating bearings and flushing particulate matter to provide long life. Two basic types of oil cooled machines are possible. Spray cooling disperses oil on the rotor and slings it off to provide stator cooling. Conduction cooling directs oil flow through passages near and around windings and laminations to extract heat. Spray cooling is usually a simpler machine that doesn't require as many dynamic seals as the conduction cooled machine when rotor windings must be cooled. The spray cooled techniques are more favorable for BLDC machines. SRM and PM designs are easily compatible with conduction cooling since the stator and stator windings are of primary concern. Oil cooled machines provide an integral means for bearing lubrication. Oil cooled machines are a common application in the aerospace community. Conduction oil cooled machines are very common in military aircraft where all attitude operation is important.

Engine coolant is very similar to the conduction oil cooled approach. This technique would take the conduction cooling principles from oil cooled systems and apply them to the machine frame of a PM machine or SRM where the principle concern is in cooling the stator windings and stator. The machine housing must have passages as an integral part that are in proximity to the stator stack. Shared engine coolant is circulated through these passages to remove heat from the stator and windings via conduction through the stator. The PM machine and SRM are ideal candidates for this type of cooling. This approach has the large advantage of not requiring any special cooling hardware, and may directly integrate with the engine. The engine radiator must be sized to accommodate and dissipate the additional heat rejection. As with the air cooled approaches, challenges exist in bearing lubrication requirements. A drawback to this technique is potential cooling leaks causing dielectric breakdowns.

The generator pole configuration is mentioned here since trade-offs in respective HFA technologies must be undertaken as detailed designs are developed. These are extensive evaluations, with many perturbations possible, especially when considering an SRM. A numerical analysis technique must be used to optimize the pole configuration versus machine weight and size. Within each HFA technology, the trade-off must be performed since each machine type is unique and undergoes a slightly different design optimization approach.

The output phase configuration is directly related to the generator pole configuration. The number of output phases must be analyzed as part of the numerical design technique to optimize design geometries and weight versus the quantity and size of conductors, and the number of poles. The PFC can also influence this aspect by assessing the impact on the input stage. As a general rule, oil cooled PFC equipment favors fewer power semiconductors, and hence fewer HFA phases, in order to attain higher packaging densities since the heat transfer efficiency is higher with oil cooling. Air cooled PFC designs experience little impact from the count of semiconductors at the input stage, and hence the number of HFA phases, since the semiconductors must be spaced accordingly to allow sufficient area for heat transfer.

Future trends in HFA designs are open to wide ranging possibilities. The new and emerging technologies may be integrated into the HFA-PFC system as they become available during the development process. One such trend is toward integration of superconducting technology to reduce copper size and generator losses. While much work is being done in this approach, it currently requires the use of expendable cooling gases that may be considered exotic when compared to the use of a tactical mobile power unit.

Bearing technology is advancing considerably with future prospects for ceramic bearings that do not require lubrication and may operate in extreme temperatures and at high speeds. Air foil bearings will provide mechanical isolation of high speed rotating equipment to reduce drag improve bearing performance. Magnetic bearings will provide similar advantages through the use of magnetic fields to suspend and locate rotating components. Consideration must be given to factors such as operating in hostile environments where there may be large amounts of fine dust, or high vibration levels.

4.4.2. MATRIX OF ELECTRIC MACHINE TECHNOLOGIES

Matrices were used to tabulate and trade-off various technical attributes, and advantages and disadvantages of the different machine types. The following matrices support the selection of favorable technologies for the power ranges described at the beginning of this section.

Table 16 compiles general advantages (PRO) and disadvantages (CON) of the various electric machine technology evaluated under this project. Included are general observations with respect to a variety of aspects. The high and low operating speed pro and con evaluations are mostly complementary.

Table 17 makes relative comparisons of the three machine technologies for numerous attributes. The ranking where applicable, follows the format from best to worst of: excellent, good, moderate, poor. The row describing short circuit information pertains to the electric machine and how it reacts when used in an HFA-PFC System.

Table 18 provides the HFA response to various fault conditions for each of the electric machines evaluated. It should be noted that potential shock and fire hazards to equipment and personnel exist if the excitation to a faulted phase is not removed. This is very similar to the existing 60 Hz synchronous machines. The SRM has the ability to de-energize an individual faulted phase. The PM machine must de-energize the faulted phase by stopping rotation. The BLDC machine must de-energize the exciter coil. It can be seen that the SRM technology offers a derated output capability during an individual phase fault, and subsequently the best alternative when considering system response to internal faults.

Table 16. HFA Technology Trade-Off

TECHNOLOGY	***PRO***	***CON***	***COMMENT***
1. Permanent Magnet	– Simple construction – No rotor windings – Low weight – High power density – PM flux excitation – No rotating exciter components – Good Motor action	– Speed limitation by mechanical integrity of PM material - imposes sleeving requirement – Unregulated output power (limited reg. available with speed) – External PFC regulation loop required – Unregulated fault current – Magnetically coupled output phases – High cost	– Based upon output regulation, this machine requires that the PFC design incorporate an independent regulation loop
2. Variable Reluctance	– No rotor windings – High temperature capability – Soft failure modes, derated operation capable – Isolated output phases (electromagnetically) – Simple construction – Good motor capability – Very High speed capability – No rotating exciter components – Subcycle transient response capability – Simple thermal designs	– Must have external excitation for startup	– HFA can be used with fixed duty cycle type PFC or independently regulated PFC
3. DC Brushless (Synchronous wound rotor)	– Startup from residual – Moderate speed capability – Simple regulation scheme – HFA regulation can be used to regulate PFC output	– Rotor cooling techniques complicate design – Rotating exciter components required (windings and semiconductors), contribute to speed limitations – Transient response limited by exciter time constant – Magnetically coupled output phases	– HFA can be used with fixed duty cycle type PFC or independently regulated PFC
4. High Speed	– Small size, magnetic design is inversely proportional to speed/frequency – High power density	– Maximum speed limitation is typically set by the mechanical integrity of the design – Higher component stresses, attention to pole tip design, poles, and rotating components – Windage losses & rotational losses	
5. Low Speed	– Lower mechanical stresses (rotational) – High reliability	– High weight – Large dimensions – High overhung moments – Low power density	
6. Modular	– Parallelable hardware capability – Cascadable common design hardware	– Slight loss of packaging efficiency	

Table 17. Machine Attributes vs. Technology

Machine Attribute	Variable Reluctance	Permanent Magnet	DC Brushless (Synchronous Wound Rotor)
Efficiency	85% to 90%	90% to 95%	88% to 92%
Machine Losses	Stator - I^2R + iron Rotor - iron	Stator - I^2R + iron Rotor - Pole face losses	Stator - I^2R + iron Rotor - I^2R + iron + rectifier bridge
Excitation	External, through main stator coils	Intrinsic by nature of PM rotor	External, through generator action of separate field winding coupling to rotating field circuit
High Speed Operation	Excellent	Moderate, especially as power level increases	Moderate-Good
Mission Completion During Fault Operation (derated operation)	Excellent - capable of derated operation	Poor - de-excite system	Poor - de-excite system
Parallel Operation for Modular Configuration	Excellent since VRM output is DC, energy transfer from inductor self adjusts to existing DC link voltage, easily summed thru ORing power diode	Excellent, will share load by voltage droop from winding I^2R loss	Good, load sharing scheme may be established, or droop mode similar to PMG machine
Short Circuit Current	Zero, excitation becomes shorted	Limited by winding impedance, PM size, fault impedance	Controllable via regulator/will try to feed fault
Short Circuit Drag Torque	Effectively zero, windage drag only	Dependent upon fault current	Controlled by fault current regulation
Thermal Limitations (using conventional material)	Stator winding insulation (typical 200°C - 250°C)	Rotor magnet material (typical 150°C)	Rotating rectifier semiconductors (typical 150°C) Rotor and Stator winding insulation (typical 200°C - 250°C)
Typical Power Rating	Fractional kW to 1000's of kW	Fractional kW to low 100's of kW	Fractional kW to 1000's of kW
Variable Speed Operation	Excellent	Good, speed affects output power available	Excellent
Engine Start Function (electric motor)	Excellent	Excellent	Good

Table 17. Machine Attributes vs. Technology (con't)

Machine Attribute	Variable Reluctance	Permanent Magnet	DC Brushless (Synchronous Wound Rotor)
Relative Cost	Low material cost Low assembly cost	High material cost Low assembly cost	Moderate material cost High assembly cost
Air Cooling	Good	Good	Poor
Oil Cooling	Excellent	Excellent	Moderate

Table 18. Electrical Fault Conditions vs. Machine Technology

Electrical Fault Condition	Variable Reluctance	Permanent Magnet	DC Brushless (Synchronous Wound Rotor)
Shorted Generator Armature Winding or Output Phase	Excellent, capable of derated operation, can de-excite individual output phases	Poor, unregulated fault currents, must shut machine down (zero rpm)	Moderate, must de-excite machine to remove fault current
Open Generator Armature Winding	Excellent, no voltage produced since there is no rotating magnetic field, operation can continue at derated output	Poor, high potential possible on open winding - can cause dielectric failure, should shut down	Poor, high potential possible on open winding - can cause dielectric failure, should shut down
Shorted Excitation Field - High side	Moderate, de-excite individual phase, continue derated operation	Excellent, condition not possible	Poor, must de-excite machine
Shorted Excitation Field - Low side	Moderate, de-excite individual phase, continue derated operation	Excellent, condition not possible	Poor, must de-excite machine
Regulator Output Transistor Failure	Moderate, de-excite individual phase, continue derated operation	Excellent, condition not possible	Poor, must de-excite machine
Regulator Logic Failure	Poor, must de-excite machine	Excellent, condition not possible	Poor, must de-excite machine

4.4.3. TECHNOLOGY DESCRIPTIONS

Top level descriptions and functional drawings are presented in this subsection to provide a general understanding of each technology reviewed. Characteristics unique to each technology and their relative impact are also discussed.

HFA-1 Permanent Magnet Machine

The permanent magnet machine discussed for this project is a version of a synchronous machine. Magnetic material is fixed to the rotor shaft, and polyphase armature windings are located on the stator. The simple configuration is illustrated in Figure 7. The Permanent Magnet Generator (PMG) is sometimes known as a Permanent Magnet Brushless DC (PM BLDC) machine. The illustration shows a 3ϕ configuration. The machine may easily be configured for a higher number of phases, such as six, in order to reduce rectifier currents and corresponding sizes when the machine is used with a PFC.

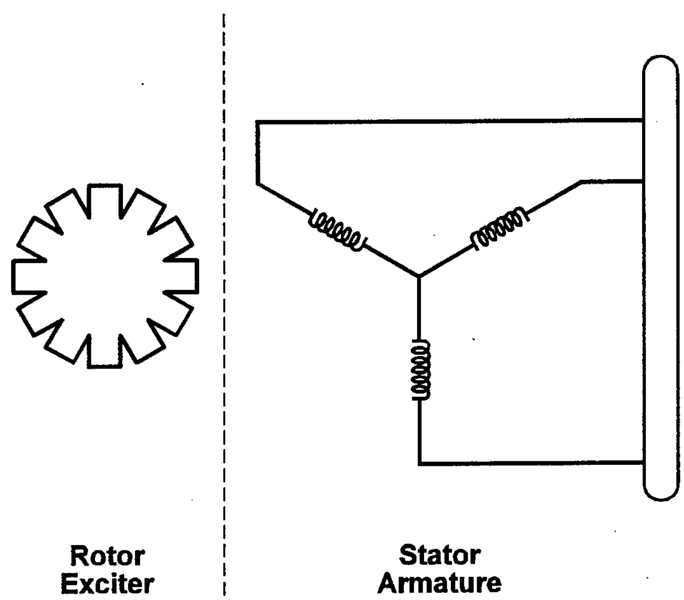


Figure 7. Permanent Magnet Machine Functional Diagram

The PMG requires no external excitation. Machine excitation is fixed and provided by permanent magnets mounted on the rotor to create rotating magnetic fields. This approach eliminates any windings associated with the rotor, and can allow a smaller machine design then wound rotor technology for lower power level applications. The PM approach, by nature, has an unregulated output under fixed operation. Relative output regulation may be achieved by controlling rotor speed which changes the flux coupled to the stator, and the resulting output voltage. More complex techniques of regulating PMG output voltages could be managed by changing the relative length of PM coupling with the armature. These techniques are complex and add considerable cost and weight to the basic machine. The PMG is most favorably used in an unregulated mode, with variable speed operation.

Recent advances in PM technology have made this machine design cost and weight competitive with many wound rotor machines. High air gap flux density is possible with PM material such as samarium cobalt magnets, and neodymium-iron-boron magnets.

Power densities as high as 0.1 lb/kW have been targeted using PM based rotor designs as early as 1985. Applications were for lightweight, airborne environments in the power range of 5 MW. Difficulties were encountered in maintaining rotor integrity during testing. Ineffective bonding of the PM to the rotor, and complicated manufacturing techniques caused failures during the rotor spin testing stages. Ultimately, the program was canceled due to it not being cost effective.

Traditionally, PM machines are very popular in the lower power ranges where their high power densities can achieve a very small design. PM machines also become more cost competitive at these lower power ranges since typical wound rotor technology in low power levels requires very labor intensive production techniques. This can be compared with a small amount of PM material required for rotor fabrication. The PM material cost is closely related to the amount of material. The PM machine exhibits a cost advantage at low power levels when compared to wound rotor technology where material cost is low, but production labor for a small machine (1.5 kW) can be the same, if not more, then for a 20 kW machine.

The PMG also provides good operation as a motor for engine start applications. As with the generator mode, a high power density is available. Only stator magnetizing currents are required since the rotor has a fixed excitation. A PFC may be used to supply the appropriate motor controlling currents. The V/f ratio of power assures operation within the machine design limitations and provides sufficient power for acceleration. Commutation of the phase currents provides the rotating magnetic field to produce rotational velocity. The phase sequence is established to provide the appropriate direction of revolution. Several control algorithm's are available for operation as a motor. One method includes using a rotor position sensor to provide closed loop feedback and control of the machine. Another method uses the machine's back-EMF to provide data on rotor position. Numerous microcontrollers are available to support each of these techniques. The position sensor technique requires a rotor position sensor to be included with the machine design at an additional cost, but provides an absolute signal on position. The back-emf approach does not require a position transducer. Rotor position is calculated from the back-emf sensed during the period when a phase is commutated off. This principle requires 120° phase conduction in order to allow a dwell time for sensing.

Limitations on PM based machines include mechanical integrity at high speeds, thermal limits of PM material, and thermal limits of stator windings. The mechanical integrity of the PM material tends to limit operating speed ranges. In order to achieve high speed operation, the PM rotor may be sleeved with a non-magnetic thermal shrink fit to preload the rotor and mitigate centrifugal stresses. This is a complex technique and adds considerable cost. Sleeving also contributes to pole face losses in the rotor causing an increase in rotor operating temperature.

Thermal limitations for this type of machine are governed primarily by the PM material and the stator winding temperature. The magnetic properties of the PM material vary linearly with temperature. The properties usually have degraded significantly once the PM temperature reaches about 150°C. Residual flux decreases as operating temperatures increase and output capability becomes considerably reduced. PM material has advanced in its capability to withstand severe environmental conditions with the usual higher cost. Operating temperature ranges have extended up to 300°C. Additionally, certain types of PM material like ceramic can be easily demagnetized during operation at low temperatures (0°C).

The stator windings typically have a 200°C upper temperature limit imposed upon them. This will provide a high reliability and long life. A full description of winding insulation considerations is given under HFA-3 BLDC Machine description since that design incorporates the most windings.

HFA-2 Variable Reluctance

The reluctance machine is a very simple design. It operates on the principal of varying reluctance along the pole paths as the rotor spins. The rotor is comprised of laminations only. There are no rotor windings. The stator is comprised of numerous poles depending upon the specific design. The functional concept is illustrated in Figure 8. This shows the machines simplicity and the minimal rotor/stator interaction.

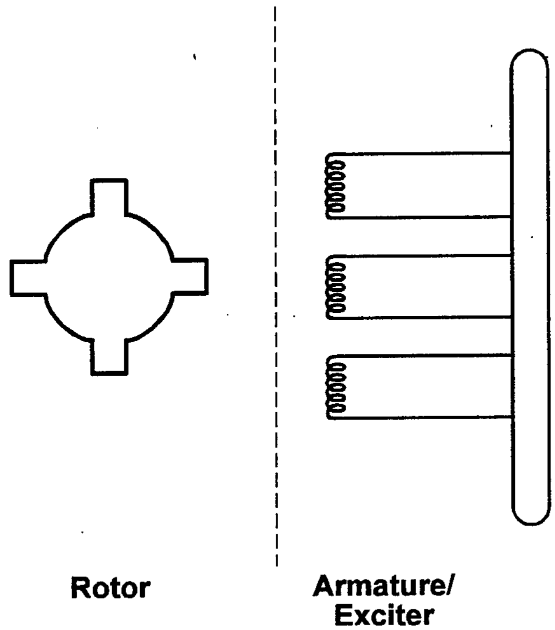


Figure 8. Components of a Variable Reluctance Machine

This section involves discussions of reluctance technology in general. Several variations on reluctance machine designs include: The Variable Reluctance Machine (VRM) which is usually referred to as the most generic. The VRM exhibits doubly saliency, having salient rotor and stator poles. The number of rotor poles may be different from the number of stator poles. The configuration is optimized to produce the largest changes in inductance with respect to the relative angular position. The Switched Reluctance Machine (SRM) which is usually a VRM operated in a closed loop fashion using a rotor position sensor. The SRM generally refers to the commutation control of the phase currents. This is the most common type of reluctance machine encountered. The output of the SRM when used as a generator is DC. A synchronous reluctance machine, sometimes referred to as a reluctance generator, uses a singly salient rotor pole configuration. A distributed set of windings in the stator is used to produce a sinusoidal AC output voltage. The most appropriate subset to refer to for general discussions is the VRM machine. Detailed designs undertaken during a Phase II effort would further refine the type of reluctance machine based upon detailed design evaluation, and selecting the most suited definition. This has a high probability of being an SRM.

A basic sketch of an SRM is shown in Figure 9. The drawing illustrates one of many possible stator/rotor configurations. Represented here is a simple 6/4 machine, meaning 6 poles on the stator and 4 poles on the rotor. Typical connections of the SRM stator pole windings are series connections of the respective pairs, supporting flux in the same direction through the rotor. This approach allows for unidirectional current excitation in the stator coils, thus providing for simplified unidirectional current control by the PFC excitation stage.

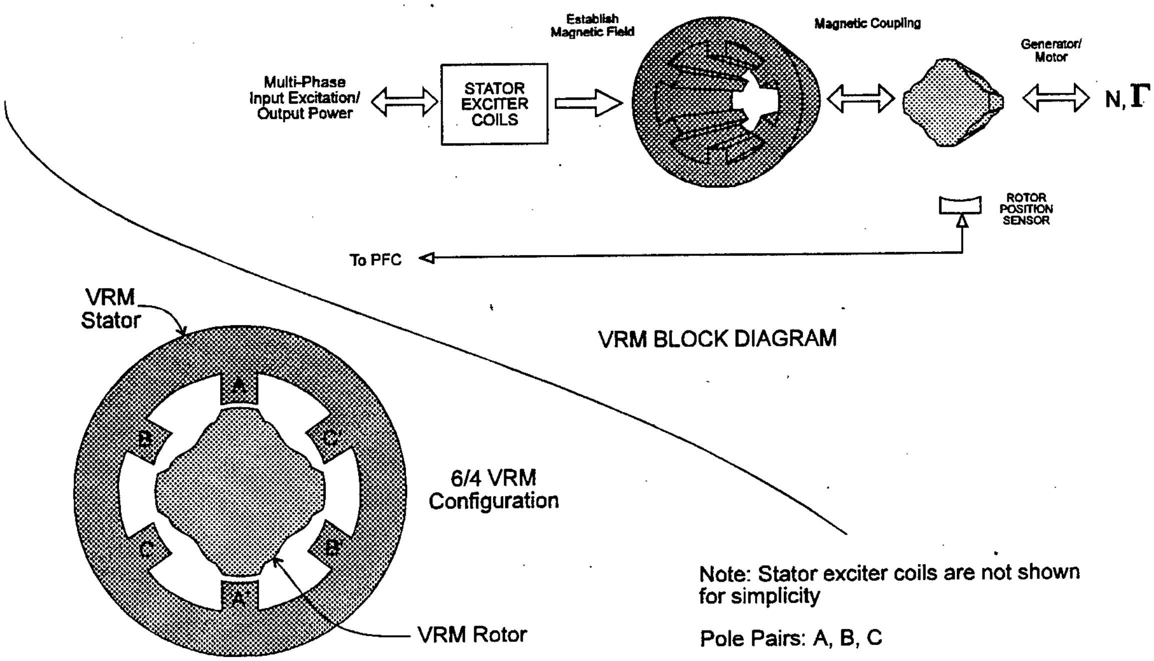


Figure 9. Switched Reluctance Machine Functional Diagram

The mechanism of power generation is related to the laws of conservation of energy. In a lossless electromechanical system:

$$dW_{elec} = dW_{mech} + dW_{fld}$$

Where:

dW_{elec} = differential electric energy input

dW_{mech} = differential mechanical energy output

dW_{fld} = differential change in magnetic stored energy

Machine excitation is provided through the stator armature windings. The armature coil is excited by momentarily applying a voltage and charging the stator inductance (armature winding). Magnetic energy is stored, as the phase inductance changes with the input of mechanical energy turning the rotor, electrical energy is produced to compensate for the change in stored magnetic energy. The magnitude is dependent upon the level of inductance as determined by the rotor position, and the level of excitation (stored magnetic energy) required by the system load. In a simple overview, the mechanical energy put into changing the rotor position, thus changing the inductance, produces a potential, and changes the stored energy in the stator winding. This change must be reflected in the change in electrical energy as defined by the summation of energy in the system. The energy is allowed to discharge through the power electronic excitation circuits into a DC bus. The operation makes the SRM technology ideal for application with PFC topologies that require a DC link.

At this time, the optimum regulation is provided by having data on the rotor position and velocity in order to provide feedback on the changing inductance. In the future, high speed Digital Signal Processing (DSP) techniques may provide an alternative to the discrete position sensor. Calculations of inductance based up the magnitude of applied voltage, phase current magnitude, and time intervals, could be used to calculate inductance and derive the rotor position by comparing the calculated inductance values with machine design inductances in a lookup table. Ultimately, in the future it may be possible to apply a neural network design to optimize control of the machine to provide improved operating efficiency and higher output power capability.

The SRM provides very good operation as a motor during electric engine start applications. Machine excitation as a motor is identical to that as a generator with the difference being the relative angular position of the rotor where the excitation is applied. Closed loop control, using a rotor position transducer, provides optimum motor control. This is the classic application of an SRM. The reluctance machine can also be operated in an open loop fashion as a motor, but this reduces efficiency. This is the classic application of a VRM. Considering that the rotor position sensor is required for operation as a generator, it will also provide the required data for optimum motor control. As with the generator mode, a future control option is to use DSP techniques to determine rotor position sensing. This approach would contribute to lower weights, smaller size, and lower costs. When designing as an electric start motor special consideration must be given to the pole configuration to assure that no angular positions are possible where there is zero torque when excited. This is usually accomplished by having a different number of stator and rotor poles.

SRM technology has received renewed interest with the advances made in power electronics, an essential component of any SRM system. Two architectures for controlling the VRM excitation in both generator and motor modes are shown in Figure 10. A single phase excitation is represented. A circuit would be used for each phase of the SRM design. Since the stator windings on pole pairs is in series, the excitation can be unidirectional. Simple PWM techniques for regulating the amount of excitation can be used. The fundamental difference between excitation in generator and motor modes relates to where the excitation is applied relative to the angular position of the rotor, and subsequently, the direction of change in inductance.

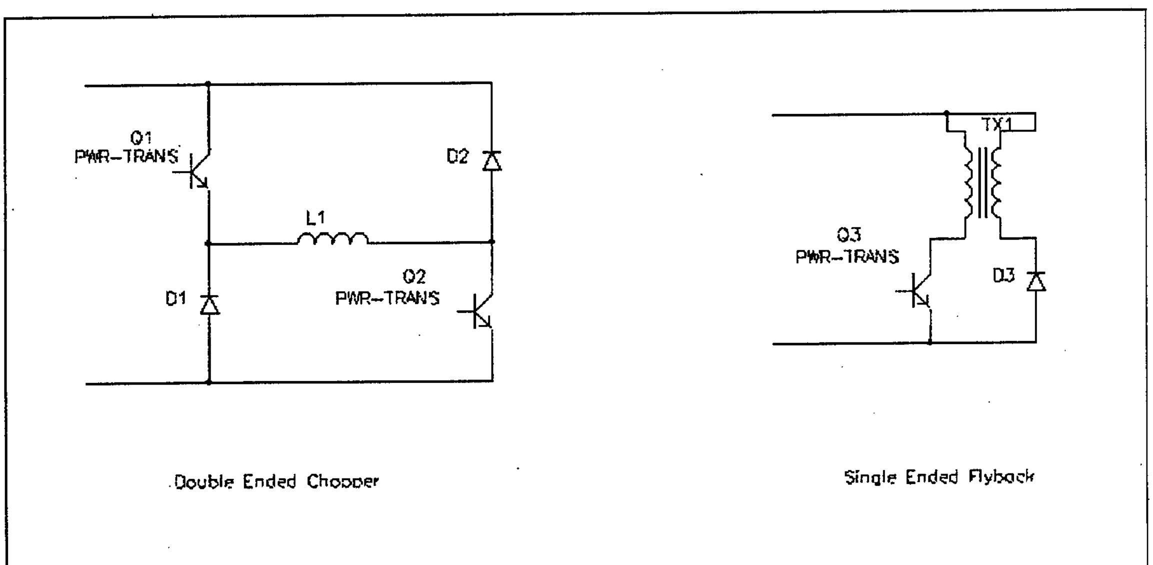


Figure 10. Control and Excitation Circuits for SRM Technology

Simulation plots for the double ended chopper show inverter currents during motoring mode are shown in Figure 11. The bottom trace is representative of the phase current. I(D2) trace shows the flywheel energy decaying by $\tau = L/R$ for the phase, which is regenerated back into the supply source. I(D1) shows the diode current in the lower diode while the phase is energized. During the off state of the PWM control, phase current continues to flow through D1 and Q2. IC(Q1) is used to control the PWM, and IC(Q2) shows the applied current to the phase.

A recent SRM prototype and demonstrator design was performed by General Electric Co. and Sundstrand Aerospace for the more electric aircraft initiative. The work was performed in the early 1990's, and has achieved power densities in the range of 0.488 lb/kW. This machine operated at a nominal 250 kW. The design was for an integral starter/generator system. Estimates of production hardware attain a 0.416 lb/kW power density at 250 kW. The machine configuration is a 12/8 with 6 electrical output phases.

General limitations for the SRM technology includes stator winding temperature limits, and critical speed design of the rotor. The stator windings are constrained by thermal limitations similar to those encountered in the PMG approach, and further detailed in the BLDC machine discussion.

The SRM technology is ideally suited to application in harsh environments. It is therefore well suited to operation in high temperature environments. The basic thermal limiting factor are the stator windings. Since these are located on the stationary housing, several methods of cooling are easily applied to the design. Convection cooling to the ambient air through radiation fins is possible, yielding a simple and cost competitive design. Conduction oil cooling can be used to remove heat from the stator stack and windings. This will reduce size and weight of the base machine.

Since the SRM rotor has no windings, or semiconductors, it can operate at higher temperatures then wound rotor machines. Thermal limitations are not normally a concern as the iron has high capabilities. The mechanical construction of the rotor is more typically the governing element for high speed operation. Insulating and bonding techniques of the rotor laminations must be capable of withstanding design temperatures and rotational forces experienced. The physical design of the rotor and poles must withstand stresses encountered during high rotational velocities. The overall rotor design must target critical speeds well above the nominal operating speeds.

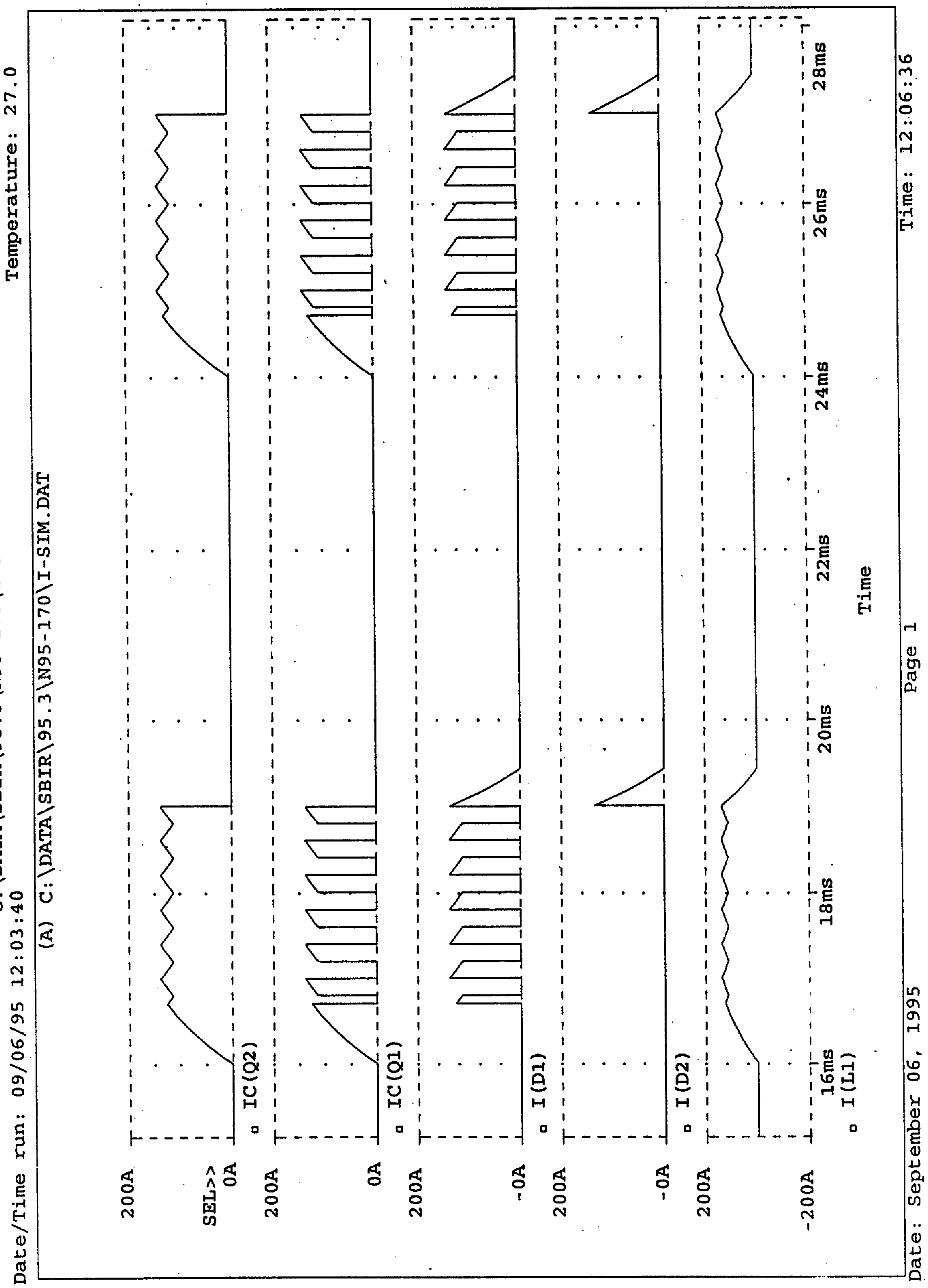


Figure 11. SRM Motor Excitation Phase Current Simulation

One drawback typically associated with SRM technology is torque pulsation generated by pole saliency. SRM machines have many possible configurations of rotor/stator pole arrangements. These have yet to be explored with the focus of reducing, if not eliminating torque pulsations. In general, torque pulsations are created by the rotation of the commutation around the stator poles. SRM machines exhibit a constant torque characteristic with respect to rotor position, when a stator pole is energized. Arrangement of poles can be made in order to sum torques through out the 360° range, and thus mitigate torque pulsations. This is more of a concern at low speed operation, such as that encountered during use as a low speed electric motor. Torque pulsation magnitudes decrease with increasing rotor velocity by 1/n when considering constant power levels. Therefore, this drawback is not a major concern when considering an HFA design.

The SRM technology has an intrinsic fault tolerance associated with the design. Since there is no rotating magnetic field as associated with traditional generators, continued excitation and derated output is possible during armature winding failures, or output interconnects. If a winding is open circuited or short circuited no voltage or current will be produced in that phase respectively. Continued operation of the machine is possible without inducing additional damage. A design that incorporates a large number of phases will exhibit only a small loss in output capability during operation under fault conditions.

HFA-3 Brushless DC Machine - Wound Rotor

The Brushless DC (BLDC) machine with a wound rotor is probably the workhorse of traditional electric power generators. The machine uses a doubly fed approach that effectively incorporates two generators into one package. This is illustrated in Figure 12.

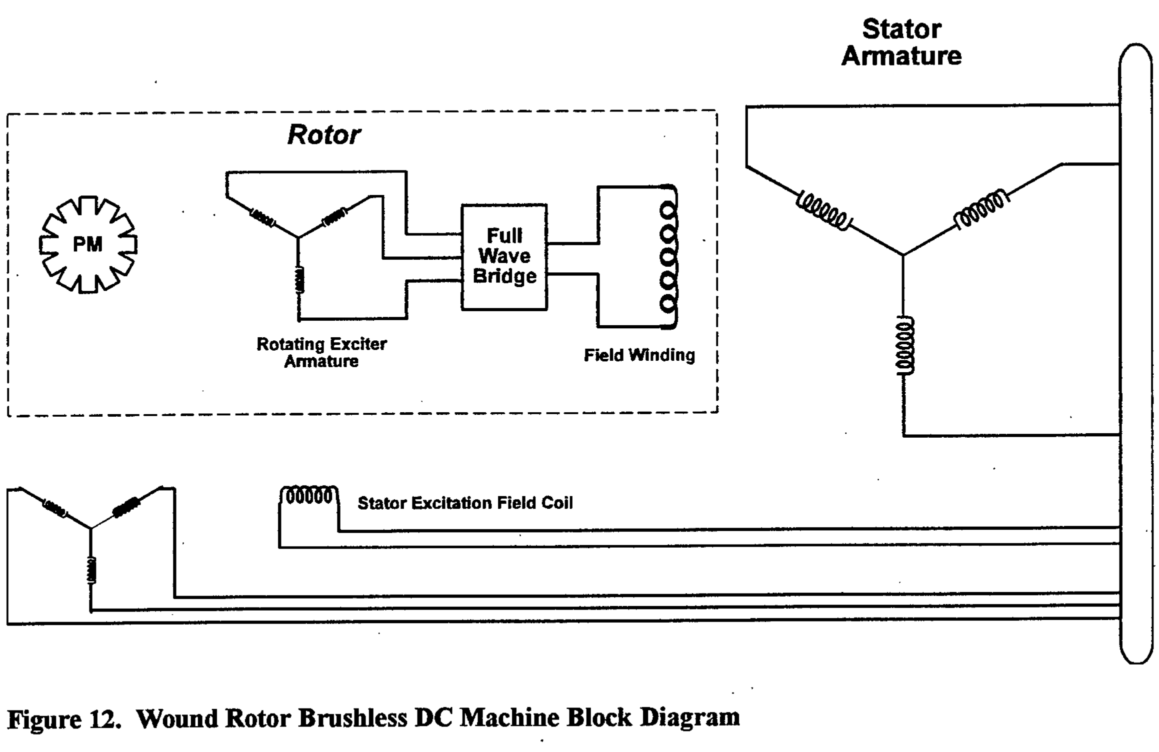


Figure 12. Wound Rotor Brushless DC Machine Block Diagram

The primary output is from the main generator. An effective generator is used to supply the field excitation energy to the rotor. The addition of a PM to supply self-contained integral excitation power actually comprises a third machine in some designs. This eliminates the need for an external power source to provide excitation, primarily during startup and in some cases during generator output short circuit conditions.

The general concept of operation starts with the rotating PM producing a low power in its armature windings. This power is applied to the stator of the excitation field in the form of DC. The energy is electromagnetically coupled to the rotor exciter armature windings. The output is passed through a full wave rectifier bridge mounted on the rotor. The output DC is then applied to the main field winding used to excite the main armature or stator output.

Excitation sources may be derived from an alternate PM source, an external energy source (such as a battery), or the generator output. External energy sources do not allow for self excitation, and may hamper system operation if the engine must be "jump-started" from a battery if the unit's primary battery is discharged. Using the generator output can require a back-up source if the system must operate under a utilization load or distribution wire short circuit. This condition is not so much a concern when the generator is combined with a PFC since the DC link voltage will not go to zero if the PFC output is short circuited. This condition must be accounted for in the design of the excitation supply. When the generator output is used as an excitation power source, initial system start-up may be accommodated by the generator residual magnetization depending upon the magnetic material used in the design. This technique is usually the lowest overall cost for excitation. The PM source allows for a highly reliable and dependable excitation source that is independent of the generator output or external sources.

The wound rotor BLDC machine has a very common application in the aerospace industry. It has experienced considerable progress in the power density of AC generators over the period from 1950 to 1980. This is best represented in Figure 13. The plot shows the increase in power density (lb/kW) over the receptive period. This chart relates to fixed frequency - 400 Hz machines. Blended into the data are a variety of operating speeds and cooling techniques.

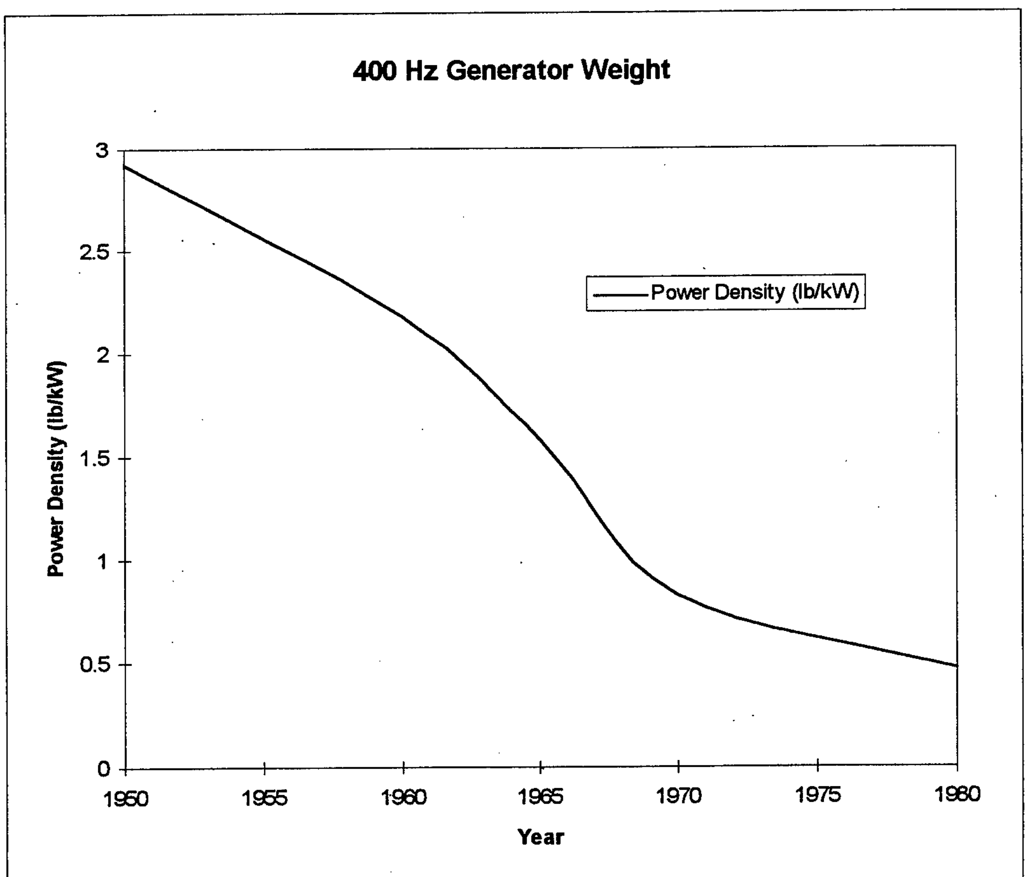


Figure 13. Generator Power Density Growth

Aerospace systems have typically only pressed the speed envelope to 24,000 rpm for a 2 pole machine. This limit is encountered due to the nominal 400 Hz aircraft buses. Traditionally, a machine was coupled with a constant speed drive (CSD) or Integrated Drive Generator (IDG) to operate at a fixed speed while the engine operated over its speed range. This combination would produce a fixed 400 Hz output. With the advent of power electronics, The speed envelope is now being pushed further as aircraft technology uses a VSCF system in place of the hydromechanical IDG or CSD and generator.

Design of BLDC machines for operation at high speeds must give particular attention to mechanically supporting rotor windings, especially when considering the end turns. The wound rotor salient pole designs must undergo detailed numerical analysis to ensure adequate design margins for stresses due to the rotational forces. This will achieve the optimum speed to weight ratios for the rotor. Additionally, the number of poles must be given careful consideration since configurations such as a two pole machine introduce additional design difficulties such as the flux path through the center of the rotor. With four or more poles the flux path circumvents the rotor center, thus easily allowing different shaft materials to be used.

Machine operating temperatures tend to be limited by the winding insulation properties and the rotating semiconductors. Magnet wire using HML or ML coatings with conventional standard epoxy impregnations is usually limited to a maximum of 250°C. The range between 200°C and 250°C derates the life of the insulation. For long life and high reliability, it is advantageous to maintain operating temperatures below 200°C. This discussion is applicable to windings in all electric machine types discussed. It is more prominent for the BLDC machine since it has a wound rotor and stator, making it more difficult to extract losses from the wire.

Ceramic insulation techniques may be used to elevate winding operating temperatures to a maximum of 400°C. This may complicate designs since localized heating may adversely affect the rotating rectifiers. Additionally, losses will go up considerably due to the copper resistance increasing. Allowing higher temperatures will reduce the amount of heat that must be removed from the winding slots. Higher operating temperatures can usually be associated with smaller sizes and lower weights, and lower efficiencies.

Losses in the wound rotor tend to provide design challenges in removing the heat from the rotating elements. Power rectifiers are usually limited to 150°C. A variety of techniques are available including conventional air cooled machines, impinging outside cooling airflow directly on the rotor components. Higher thermal efficiencies are achieved using oil cooled designs. These may be spray cooled or conduction cooled machines. Traditionally, spray cooled designs offer a simple, cost effective approach. The drawback is slightly less effective cooling efficiency then with conduction cooling. Conduction cooled machines provide the most effective and efficient method of heat transfer, thus typically yielding the most compact and lightest machines. Conduction cooled machines become highly complicated, especially when channeling oil through the rotor to flow into the rotor stack and near the rotor windings. Naturally, the machine cost reflects the additional complexity.

Operation of the BLDC machine as a motor is more complex then the previous two technologies. The primary reason is that a magnetic field must be established in the rotor. This is done by applying AC power to the exciter stator. This energy is coupled to the exciter rotor through transformer action while the rotor is at a standstill. Once rotation has begun, the excitation energy is bolstered by generator coupling action of the exciter power. Excitation energy is limited at this point by the exciter field impedance. Once the rotor is magnetized, a rotating field is established in the stator in a similar fashion to the PM and VRM machines. The rotating field must be in synchronism with rotor velocity, and within phase limitations of the rotor poles. Rotor position information may be derived in a similar fashion as with the PM machine using either a discrete rotor position transducer or the back-emf sensing technique.

HFA-4 Induction Generator

This technology is based upon the traditional induction machine operation. Excitation as a generator is performed through the stator armature and coupled to the rotor by transformer action. The rotor is typically a squirrel cage configuration. No rotating rectifier components or the associated rotating exciter field is required, thus potentially providing for a high reliability operation.

This technology is considered unfavorable due to the complex excitation algorithms or control loops required to operate over varying loads and speeds. The changing slip frequency of stator to rotor coupling complicates the control loop. Even though the varying output operating frequency is transparent to the system output due to the PFC, the induction generator is considered unstable when operating over varying loads and a wide speed range.

4.5. *ENGINE OPERATION REVIEW*

An integral part of achieving the weight savings associated with the HFA-PFC is the interface with the engine. Certain aspects directly affect the weight savings and estimates, other aspects have more ambiguous benefits. High speed operation and using the starter/generator architecture can produce direct weight savings and improve MEPS mobility. Using the VSCF mode of operation will reduce logistical support for the MEPS and field troops. VSCF operation will reduce fuel consumption, thereby decreasing the required quantity of fuel to support MEPS equipment.

A summary of optimum engine interfaces is presented in Table 19.

The information presented from work done under this task is to illustrate the feasibility and consider interface issues of the optimum HFA-PFC System approaches. The data is from conceptual design work. It is to set the stage for possible preliminary designs. The detailed hardware design would be undertaken during a development effort.

The HFA-PFC System is well suited to operation with varying engine interfaces. The direction of generator rotation is no longer important since power is being conditioned by the PFC. The output power is transparent to the phase rotation of the generator output. This makes considerations of the gearbox output pad direction immaterial.

Table 20 presents trade-offs considered during the evaluation of different engine interface alternatives.

Table 19. Optimum Engine Interface Configurations

	POWER RANGE				
TECHNOLOGY	***0.5 - 3.0 kW***	***5 - 15 kW***	***20 - 60 kW***	***100 - 200 kW***	***500 - 1000 kW***
MECHANICAL INTERFACE	Speed Increaser/ Gearbox	Speed Increaser/ Gearbox	Speed Increaser/ Gearbox	Speed Increaser/ Gearbox	Speed Increaser/ Gearbox
CONTROL INTERFACE	VSCF	VSCF	VSCF	VSCF	VSCF
ENGINE START	N/A	Starter/Generator	Starter/Generator	Starter/Generator	Starter/Generator
COOLING	Independent/ Air Cooled	Gearbox/HFA-PFC Closed Oil Management System w/ oil - engine coolant heat exchanger	Gearbox/HFA-PFC Closed Oil Management System w/ oil - engine coolant heat exchanger	Gearbox/HFA-PFC Closed Oil Management System w/ oil - engine coolant heat exchanger	Gearbox/HFA-PFC Closed Oil Management System w/ oil - engine coolant heat exchanger

Table 20. Engine Interface Technology Trade-Off

TECHNOLOGY	PRO	CON	COMMENT
1. Speed Increaser/ Gearbox	– Allows low weight generator design – Provides integrated oil management system	– Additional system component required	–
2. Main Engine Shaft Output	– Reduced system components (no gearbox)	– Low speed output, maximum realistic gen frequency 200 - 300 Hz – High weight HFA, system	–
3. VSCF Control	– Reduced fuel consumption – Reduce engine stress, longer life, lower maintenance – Lower thermal emissions during periods of light load – Lower acoustic signatures at reduced load – Can provide lower HFA design weight if HFA is designed to engine speed power curve	– Longer engine transient response to utilization load changes – Additional control loop	–
4. Fixed Speed Operation	– Simple control algorithms – Faster engine transient response to utilization load changes	– Higher fuel consumption associated with engine operating continuously at higher power output – Higher stress on engine & HFA	–
5. Starter/Generator	– Eliminates existing DC starter – Lighter weight MEPS – Integrated engine operation - automatic start	– Input converter stage required in PFC	– The input converter stage also supports UPS operation and electronic battery charging
6. Integrated Oil System	– Share existing engine based oil system, economies of scale provide slightly lower weight	– Oil contamination – Overloading engine oil system, increase size and weight to compensate	
7. Independent Oil Management System	– Closed loop, high quality system – Reduced maintenance	– Additional components	– Integrated with gearbox

4.5.1. DESCRIPTIONS OF ALTERNATIVES

The following descriptions offer several candidate solutions to engine interface challenges. These are intended to provide a general overview of the concepts. Detailed designs must be undertaken during a development effort that may somewhat change the configurations. The options are shown to demonstrate feasibility of the alternatives.

Mechanical Interface

In order to achieve the largest weight savings for the HFA design, it should optimally be run at a high speed. Since engine operating speeds are generally limited to 2000 - 3000 rpm maximum for continuous duty gas and diesel fueled engines, a speed increaser is required. Once a speed increaser is required, many options may be considered. An offset design may be optimum to configure internal gearing. This would provide a dual face mounting provision for a modular generator drive architecture. The concept is best illustrated in Figure 14.

The figure shows the general concept of the interface. Mechanical supports may ultimately be required for structural integrity. This will depend largely on the equipment weights, transportation environment, and overhung moment. Envelope changes may accommodate oil reservoirs, gear and bearing support, and mounting provisions. These details will be addressed in a hardware design phase using computer based numerical analysis programs to assure lightweight designs while providing mechanical integrity. Lightweight aerospace designs are in use aboard aircraft that provide multiple power take-offs for 150 kW in approximately 75 lbs.

The concept figures presented in this section show the speed increasers populated with the maximum count of HFAs. A single speed increaser design will be used for each power category as defined in the modular approach. For example, the 100 - 200 kW category will have a speed increaser rated for 200 kW. This unit is used with either the 100 or 200 kW configurations. When a single HFA (100 kW) configuration is used, the vacant mounting pad will be capped with a plate to seal the speed increaser.

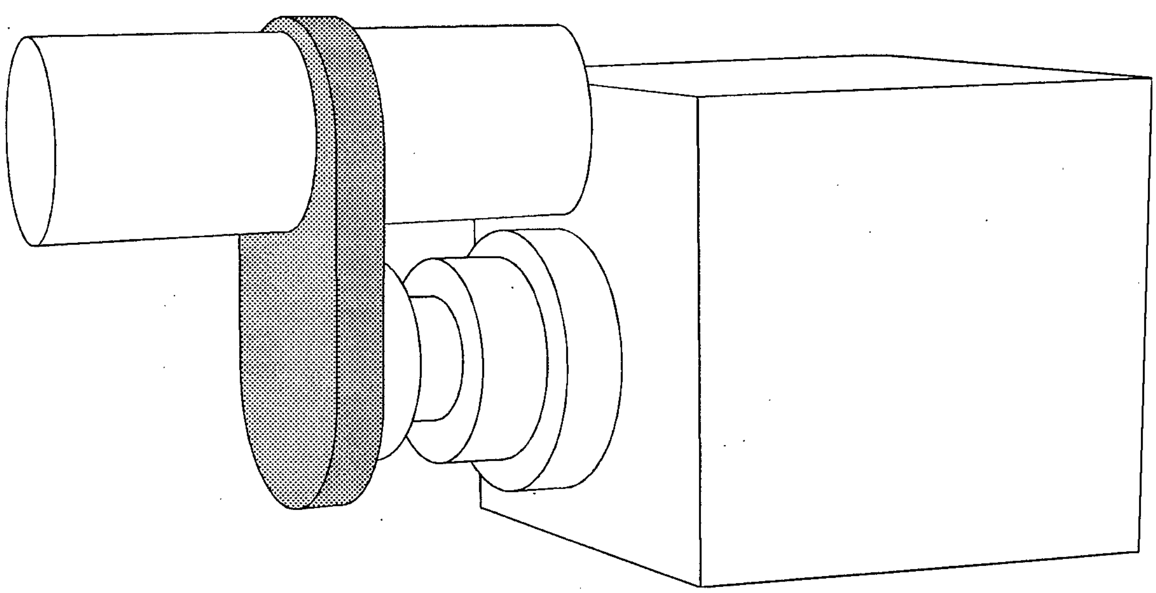


Figure 14. Speed Increaser/Gearbox Providing Dual Mounting for Modular HFA-PFC System

The speed increaser will require lubrication and possibly cooling. An oil management system may be integrated into the speed increaser design, resulting in a gearbox that supplies multiple functions. The oil revision, pump and filter may be contained within the gearbox design. Ports can be provided to supply cooling and lubricating oil to the HFA designs. External ports may be supplied to connect cooling lines to the PFC cold plates. The oil management schematic shown in Figure 15 illustrates the oil flow and interconnections through the HFA-PFC System.

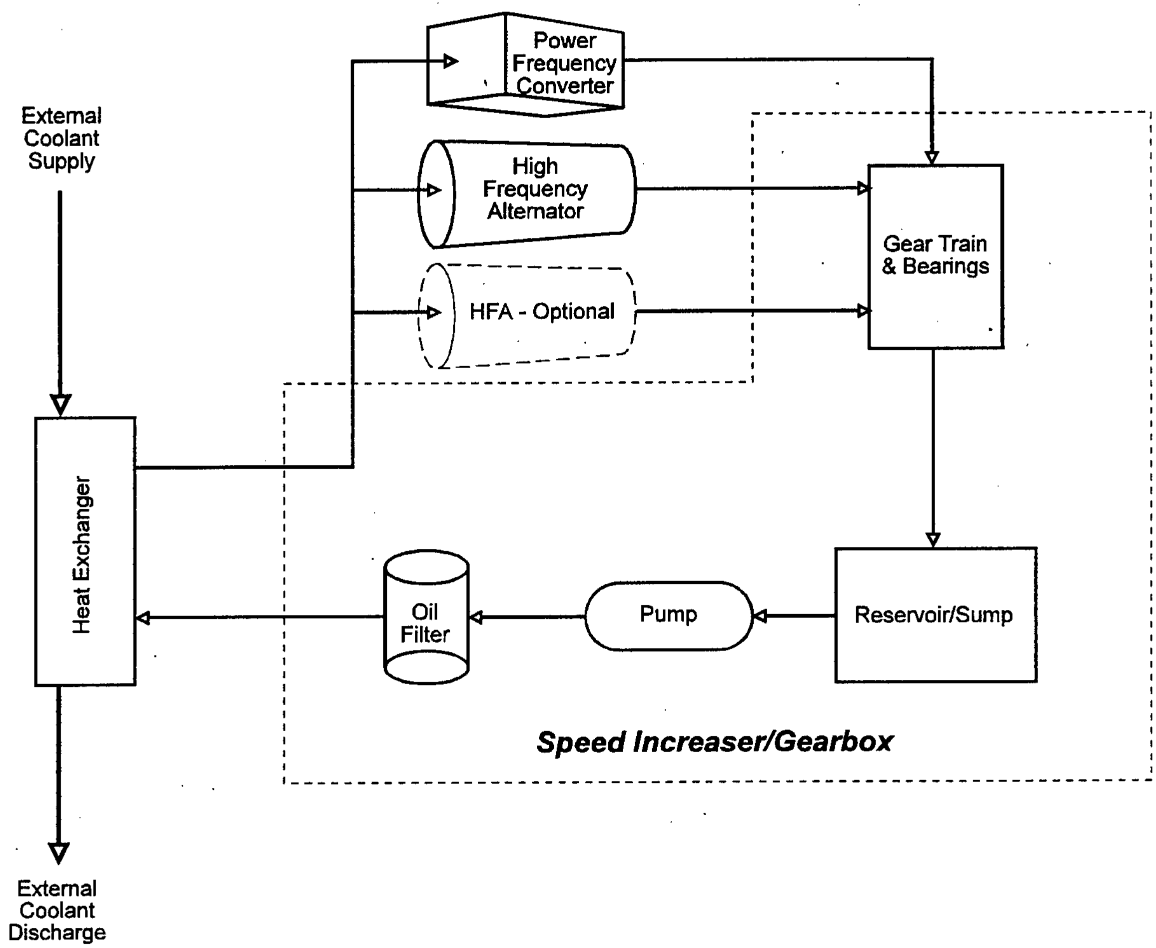


Figure 15. Simplified Oil Schematic

The oil schematic shows the integration of a heat exchanger to dissipate heat rejected to the oil into the engine coolant for dispersion into the ambient environment through the engine radiator system. The diagram shows the main elements and oil flow paths of the oil management system. Check valves, oil fill ports, and level indicators, etc. were omitted for simplicity. Ultimately, these components must be integrated in a detailed design as required.

The oil to engine coolant heat exchanger may be an external component to the system, or it may actually be integrated as a submodule in the gearbox. The engine cooling system must be capable of dissipating the additional heat generated by the HFA-PFC System losses. An overall efficiency for the HFA-PFC System, from mechanical engine shaft input to PFC electrical output can be approximately 80%. The remainder of this power, is the losses rejected to the oil. In a closed oil cooling system, the efficiency of heat transfer to the cooling oil is several orders of magnitude better then the efficiency of heat rejection to the ambient due to convection. So, for analysis, it may be assumed that all the heat is rejected to the oil. These assumptions also provide a slight design margin for the heat exchanger and the HFA-PFC components.

Optionally, the heat exchanger may be independent from the engine cooling system. The implementation may be similar to that of the engine's radiator system, where the heat is rejected to the ambient. This approach consumes additional weight and size as a dedicated fan and radiator are required.

A closed loop oil management system is the best alternative for lubrication and cooling. High quality oil may be used that will retain its characteristics over a long period of time. Synthetic oils such as MIL-23699 provide high lubricating qualities, good heat transfer qualities, and good viscosity during cold temperature operation. This is in comparison to using a shared oil system with the main engine. The nature of the internal combustion engine degrades oil at a high rate. Use of this oil may lead to contaminant build up in the HFA-PFC system, reduced bearing life, and less efficient cooling.

The use of a speed increaser must consider the additional load placed on the engine. This will have a very minimal impact at normal operating temperatures and high temperatures. Compatibility, particularly with engine start at cold temperatures, will have to be verified for respective engine and starter designs.

The speed increaser/gearbox concept may be extended to support three HFA modules as required by the two midpower categories. This concept is shown in Figure 16. The same considerations to an oil management system apply to this and other alternate installation configurations.

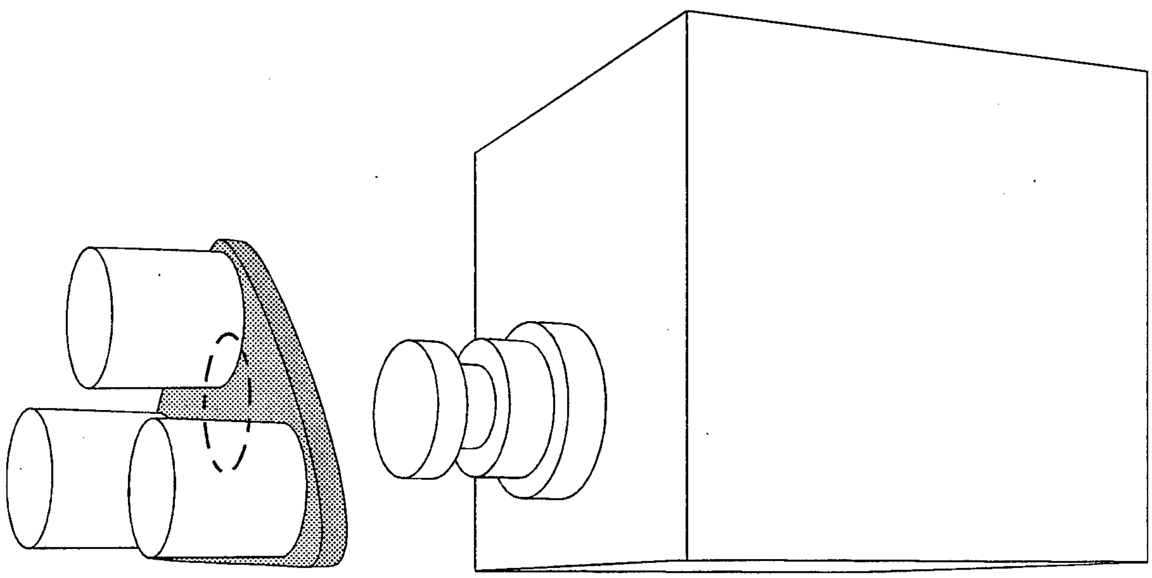


Figure 16. Triple HFA Module Mounting Configuration for Speed Increaser/Gearbox

A further variation on the gearbox is to change the direction of power outputs relative to the input power. An example is shown in Figure 17. This option may be favorable depending upon the installation space available, and the engine arrangement.

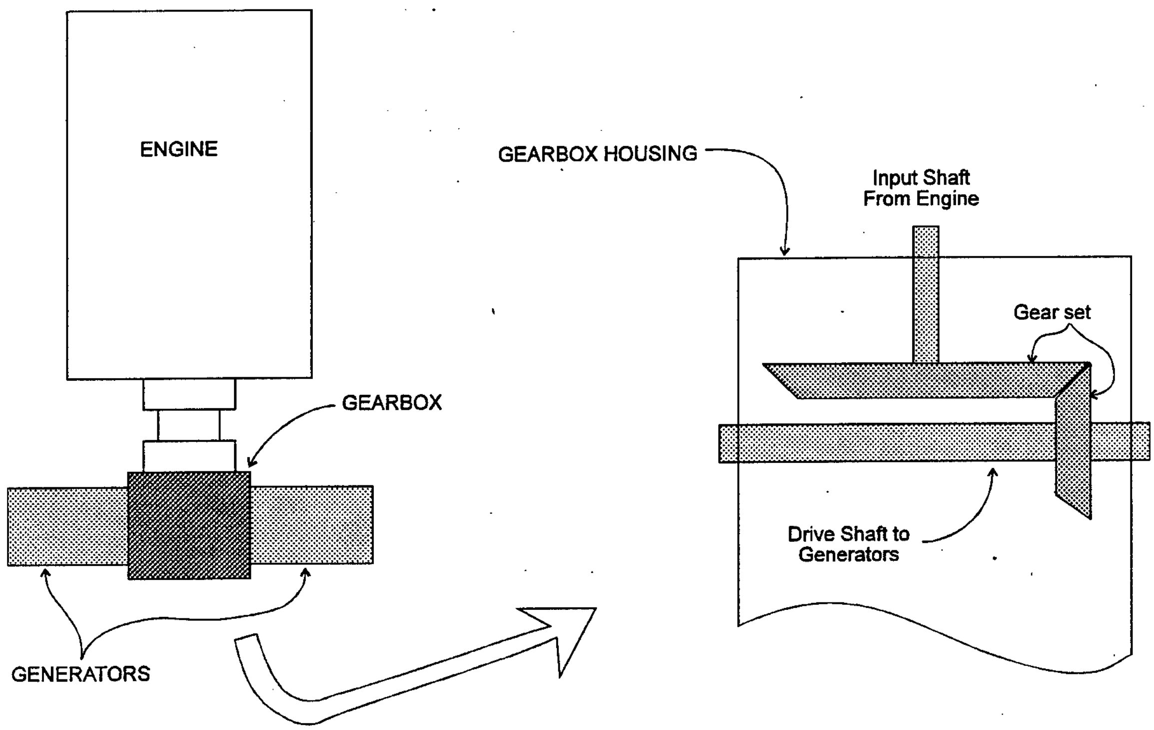


Figure 17. Right Angle Gearbox Option

The diagram considers possible arrangements of gears in order to effect the required right angle transition. It is intended to illustrate the concept feasibility. A detailed design would be undertaken during a development effort where proper gear design and bearing supports would be integrated. Lubricating paths would be realized, and any required cooling.

Variable Speed Constant Frequency

In order to accommodate the VSCF operation of an HFA-PFC architecture as previously described, control of the engine speed is necessary. In many typical VSCF applications the engine speed is set by the power required for vehicle propulsion. This project addresses VSCF operation as an approach to reduce fuel consumption. The engine speed will be a function of utilization load. Many benefits can arise from VSCF operation including:

- Reduced fuel consumption
- Low Acoustic Emissions
- Lower Thermal Signatures
- Reduced engine wear
- Reduced generator wear
- Reduced engine maintenance (oil changes)

These result in lower life cycle costs for the equipment, lower detection possibility by adversaries, and improved readiness. Thermal signatures are directly related to the system losses as a function of efficiency and system loading. Likewise, acoustic emissions will be related to the operating speed and load level.

Several challenges must be overcome such as the engine transient response time. Even though the HFA-PFC transient response is fast, in some architectures, subcycle, the engine may stall if it is not at the required output power level. One solution is to limit engine operating speed range and HFA-PFC transient response to that which, when combined, the system can respond within the time specified in MIL-STD-1332. A standby mode may be offered that will allow the engine to idle when the user selects, and supply a minimal load.

Another approach is to integrate a smart control system, where heavy utilization loads send a control signal in advance of energizing. The control signal may be a low level current signal in proportion the utilization load magnitude. The HFA-PFC would be able to ramp up to the required operating speed to achieve the necessary engine output. This approach may be valid for new hardware designs. It has the advantage for integrated use with radar sites and fire control systems. The hardware may be in standby mode until the system is needed and energized. This would reduce acoustic emissions and thermal signatures while in standby, making detection of equipment more difficult.

A similar approach could be effected by using smart power management to automatically determine the connected load. This would be a self contained design and not require any communication with the utilization loads.

A manual mode or override may be required where the user selects the output power level where the engine should operate. The user would know if a coffee pot is running, the MEPS could be set at a low output, and subsequently quite mode.

Another solution is to build a power curve control into the HFA-PFC where the output power (voltage) will be limited based upon engine speed. This curve will be followed until the engine has had sufficient time to ramp up to its required speed. This will prevent the engine from stalling upon a heavy load application. The approach would have a response similar to existing engine generator sets as their load transient is controlled by the engine throttle.

VSCF control will be implemented by electrical actuators when integration with throttle plate speed control systems is required. New Digital Engine Control (DEC) technology will provide the opportunity to for electronic control of the engine speed. A low level current bias signal, proportional to the load setting, can be sent to the engine control system. The engine controls will then set the appropriate engine speed.

Starter Generator

The integral starter generator concept uses the generator as a motor to provide main engine starting power. This eliminates the existing DC starter further reducing system weights. This function requires the same components as a UPS front end would require. Once one function is integrated, the second should be implemented.

The elimination of the DC starter also removes the maintenance associated, since brush type electric machine tend to be a high maintenance item.

Once a UPS function is realized, an electronic battery charger should be included to maintain the reserve battery at full charge. Otherwise, a trickle charge from a rectified tap on the output should suffice.

4.6. POWER SEMICONDUCTOR SELECTION

The power semiconductor industry is highly dynamic and is being driven by a recent interest in applications in high volume markets such as automotive and industrial. As the applications of these power semiconductor components increases, cost will be driven down, and capability will be expanded. The supply and demand side of this market are mutually reinforcing the direction toward high power capability and density, and lower costs. Further enhancing the lowering cost are improved manufacturing methods and process technology. Demand is being driven by continuous pressures for improved operating efficiencies, and improvements in system reliabilities by replacing mechanical and electromechanical devices with solid state counterparts.

Device technologies that are currently available for use in production quantities are shown applicable to their appropriate power ranges in Table 21. This table represents immediate application of available technology if hardware was fabricated in the near term.

Table 21. Power Semiconductor Application Matrix

	POWER RANGE				
	0.5 - 3.0 kW	5 - 15 kW	20 - 60 kW	100 - 200 kW	500 - 1000 kW
TECHNOLOGY	Power MOSFET	IGBT	IGBT	IGBT	IGBT

A timeline shown in Figure 18, best depicts the current state of power semiconductor development and the potential future growth. Recent experience and research indicates that Mos Controlled Thyristors are presently have limited available for semi-prototype hardware. This is expected to increase as new versions of the MCT are introduced.

Naturally, as the new devices are introduced, they may become recommended for use depending upon their operating characteristics.

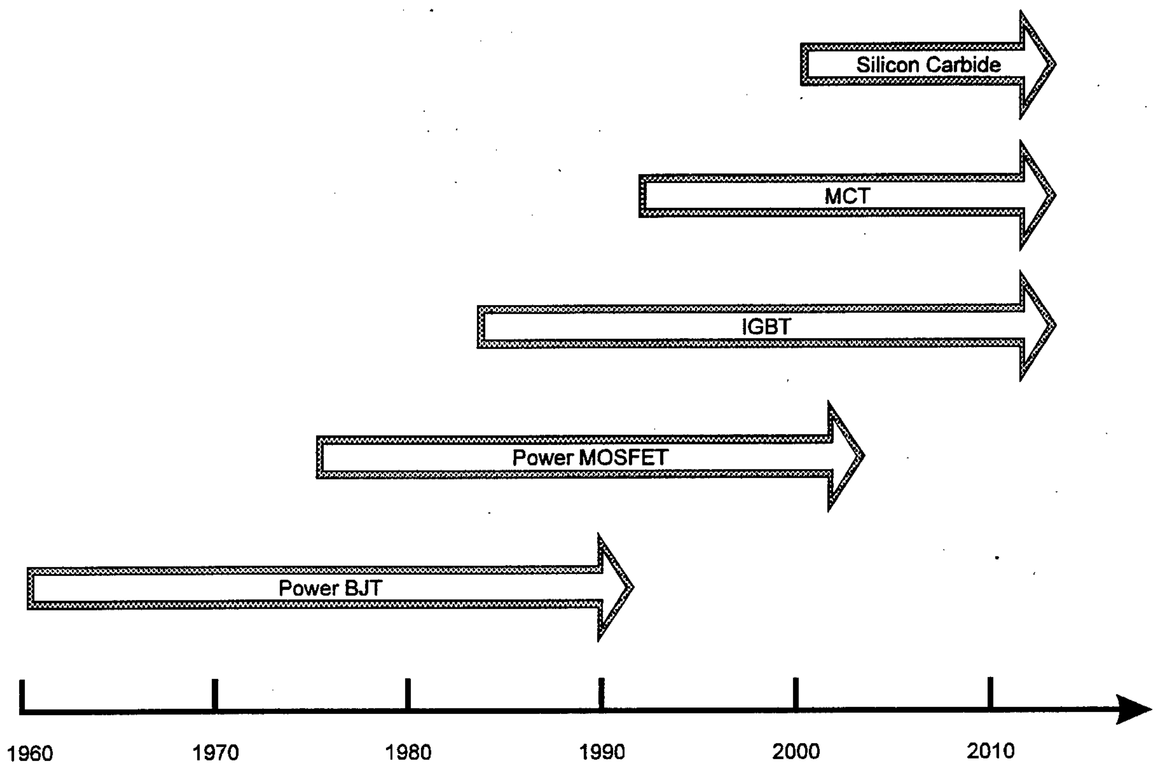


Figure 18. Power Semiconductor Technology Timeline

The timeline represents when most technology became available or predicted technology will become available. Production level fabrication can take longer. The silicon carbide technology will be used to replace the fabrication material of devices presently made with silicon. The MCT technology has been available, but it is difficult to obtain quantities due to production yield on the devices. IGBTs are a standard application in power converters.

The power semiconductor growth encompasses the discrete components such as power switching transistors and rectifiers, support components such as multilayer ceramic capacitors, and integrated controllers for controlling the power switches. The power semiconductor market is forecasted to double sales in the next five years.

4.6.1. IDENTIFICATION OF ALTERNATE TECHNOLOGIES

Conventional power semiconductors available for present applications include:

IGBT	Insulated Gate Bipolar Transistors
GTO	Gate Turn-Off Thyristors
BJT	Bipolar Junction Transistors
Power MOSFET	Power Metal Oxide semiconductor Field Effect Transistor
MCT	Mos Controlled Thyristor

One potential advance in power semiconductor technology is the use of Gallium Arsenide (GaAs) as a device fabrication material instead of traditional silicon. This has the ability to extend operating junction temperature to 300°C from the typical 125°C maximum presently available. GaAs exhibits a larger energy gap, translating into smaller intrinsic carrier densities, thus leading to lower on-state resistances then silicon based devices. GaAs based rectifiers are now available, and the material will continue to migrate into other devices as yield and purity improve on processing the raw material.

Silicon Carbide (SiC) is another material that even has a larger band gap then GaAs. Work done by the NASA Lewis Research Center on SiC based FETs has demonstrated operation at 600°C. This material will extend the operating temperature ranges and improve radiation characteristics, making the device suitable for use in hostile environments. The first commercially expected devices would be FET technology with ratings of a few amperes and several hundred volts. [11]

In addition to power semiconductors, evaluation of new supporting components should be monitored for future developments. Metglass magnetic material offers new approaches to magnetic design for applications in light weight designs with high flux capability.

Multilayer ceramic capacitors are improving capacitor performance for high current, high frequency applications.

All power semiconductor applications must assess the need, and usually require, the use of snubber networks. These aid in removing switching losses from the device. Most importantly, a properly designed snubber maintains the device's operation within the allowable SOA.

4.6.2. MATRIX OF APPLICATIONS

Table 22 shows typical application characteristics for a variety of power semiconductors. These are based upon presently available devices and published data sheets.

All Drive Signal Requirements mandate isolated drive circuits when devices are referenced to different potentials.

The maximum switching frequency is rated for hard switched circuits. When the devices are used in soft switching applications, their maximum switching frequency can typically double.

Appendix F shows published data on a several aspects of power semiconductor applications. The chart by POWEREX represents typical applications of technology to various power levels versus the nominal operating frequency. [18]

Table 22. Power Semiconductor Technology Comparison

	IGBT	*MCT*	*GTO*	*BJT*	*Power MOSFET*
Production Availability	Now	Difficult to obtain	Now	Now	Now
Current Ratings (A)*	600	60	4000	1000	50
Voltage Ratings (V)*	1700	1000	4500	1200	1000
Typical Power Application	– Power converters – Motor Controllers – UPS	–	– Utility line applications – HVDC	– Older power supplies – Older power converters	– High frequency power supplies
Forward Voltage Drop (at rating)	2.0-2.5 V	1.0 V	1.35-2.0	2.0-3.5	2.0 ohms
Turn-Off Times	110ns	1.5µs	10-30µs	10-20µs	35 ns
Drive Signal Requirements	Voltage	Voltage	Current	Current	Voltage
Typical Maximum Switching Frequency	40 - 60 kHz	10 kHz	< 2 kHz	10 kHz	MHz
Intrinsic Flywheel Diode	Yes	No	No	No	Yes

* These ratings are not necessarily applied at the same time

4.6.3. TRADE-OFF COMPARISON FOR POWER RANGES

Insulated Gate Bipolar Transistors

The Insulated Gate Bipolar Transistor (IGBT) has become the recent mainstay for high power conversion systems. This device is voltage driven, with a high gate impedance, and can control high currents, with high sustaining voltages.

These devices exhibit good paralleling capability. Gate drives and circuit layouts must be matched to equalize impedances, especially during switching when higher order harmonics enter into play.

According to a recent article in the IEEE Spectrum, the power ratings of IGBTs have been tripling every two years. The rapid capability increase is due to the ability to scale the device's voltage rating without affecting the on-state voltage drop. [1]

Mos-Controlled Thyristors

The recently developed Mos-Controlled Thyristor is targeted at reducing on-state voltage drops to 50% of the equivalent IGBT rated device. MCTs are advantageous in applications where conduction losses dominate, and a large SOA is not required. These are good candidates for resonant architectures.

Current p-channel technology devices do not support a large forward biased SOA. Anticipated development of the next generation device is supposed to improve this characteristic. An n-channel device marked for development is reported to significantly improve the forward biased SOA to the point that the device will be suitable in hard switched applications. Maximum switching frequencies of this device are expected to be near 200 kHz. The device is expected in the late 1990's.

The device also shows promise for application in higher temperature ranges. Depending upon the package limits, the operating junction temperature can be as high as 200°C.

The device reportedly can be paralleled when its forward voltage drop and turn-on times are matched, and particular attention is given to circuit layouts and thermal dissipations. The circuit layouts affect the line inductances, ultimately impacting the ability of the devices to share load currents during switching.

One of the main challenges that persist with this device is the ability to procure parts. Production yields appear to restrict the quantities available. Several companies have withdrawn from MCT technology due to the poor SOA capability.

Gate Turn-Off Thyristors

Gate Turn-Off (GTOs) thyristors have usually dominated the very high power applications encountered in high voltage DC transmission, utility power distribution, and very large motor controllers. These devices lack the operating frequency capability that allows other devices such as IGBTs to produce size and weight reductions in power converter applications.

Work is being done to extend the power handling capability of these devices to 9 kV and 4000 A. Reportedly, advanced development is well under way on 53 mm, 77 mm, and 100 mm diameter die. Developmental work on thyristor with a 125 mm die rated for 6000 A and 6500 V is under way and expected to be commercialized in two years. [1]

Bipolar Junction Transistors

BJTs are current driven devices that require complex drive circuits to supply a base drive signal. Regenerative base currents may be used to aid in switching the devices at low collector currents. The base drive circuit must also supply the transistor reverse base current, I_{B2}, during turn-off. The base drive circuits can become complex, even though they can be implemented in hybrid microelectronic circuitry.

BJTs do not parallel well due to a negative temperature coefficient. In a parallel operation, when one devices carries more current, it operating temperature goes up, the on state resistance goes down, and it begins to carry more current. This continues the rise in temperature, thus regenerating the current hogging.

Power MOSFETs

Power MOSFETs usually have an ideal application in high frequency circuits (>100kHz) due to their extremely fast switching times (<100 ns). They tend to have increasing on-state resistances with higher sustaining voltages and their application falls out of favor at higher power levels. These devices are usually used in high frequency, low power supplies.

Power MOSFETs are ideal candidates for paralleling devices due to their positive temperature coefficient for on-state resistance.

Power MOSFET ratings have been reported to double every two years.[1]

Rectifiers

Rectifiers are a simple devices that tends to be ignored in many power conversion circuits. These devices can be the source of unwanted additional losses or EMI. Specific consideration must be given to the selection of these devices when used in high frequency switching applications. The input frequency associated with a HFA can be a nominal 2 kHz. This is respective of a 500µs period. General application power rectifiers can experience a reverse recovery time, t_{rr}, of 15µs, equivalent to 6% of the conduction period. During this time considerable losses may be generated, increasing the heat rejection of the PFC. This condition is further amplified when considering high switching rates of PWM or resonant mode inverter (20 to 40 kHz).

If the rectifiers have a sharp recovery knee, the harmonics generated during the reverse recovery can contribute significantly to the EMI emissions. A trade-off must be made in the device's characteristics for a soft recovery vs. recovery time.

Some of these characteristics may be improved through the use of snubbing circuits.

Consideration for use in low voltage applications may bias the choice toward Schottky diodes, which exhibit very low on state voltages, helping to improve efficiencies in high current circuits.

4.7. Cooling and Packaging

Many of the cooling and packaging features were covered under the respective subtopics for each component. This section provides a summary of the optimum configurations as presented in Table 23.

The general installation may be illustrated in Figure 19. Concepts to support high mobility and rapid deployment must be integrated in the packaging design with respect to equipment set up and service.

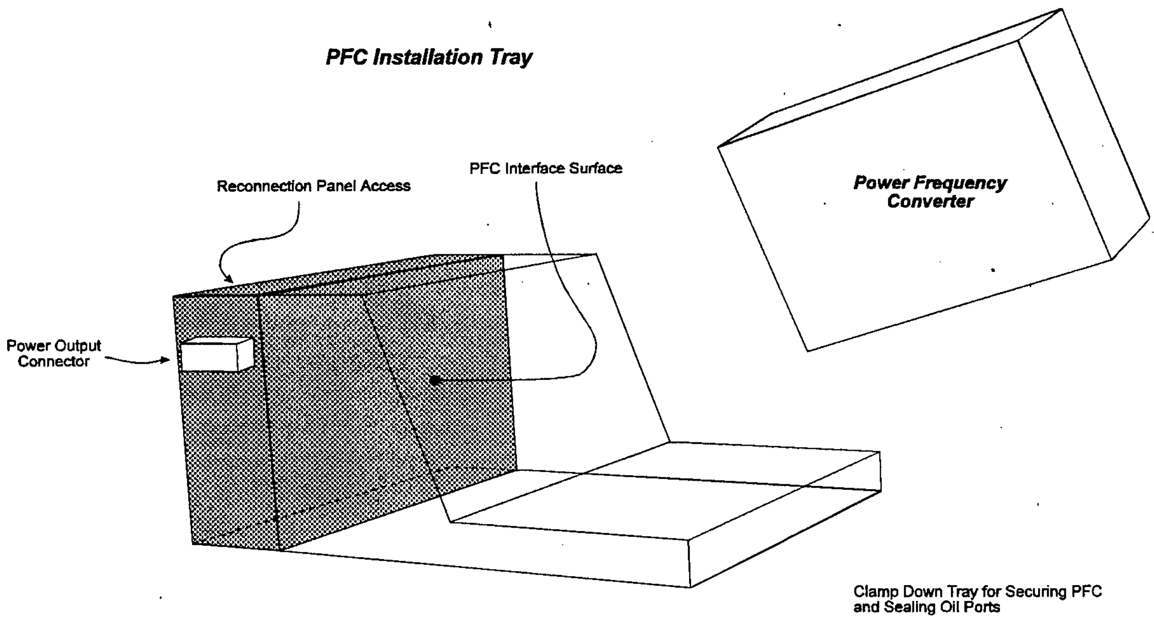


Figure 19. PFC Installation Tray Concept

The designs include a standardized rack approach for mounting the PFCs on the engine generator set. This rack contains the equivalent to a backplane which houses the interconnect wiring among the PFCs. Enclosed in a portion of the backplane is the terminals available for reconnection of the HFA-PFC System output. Distribution wiring plugs into the tray for transmission of power to the loads. The oil connections to the HFA are also made through the mounting tray at the mating surface with the HFA cold plate. The integrity of the oil connections and electrical connections is provided by securing the HFA in place with bolts.

The generators are mounted to the gearbox individually for modular replacement or repair. All oil connections are made through the interface plate with the gearbox.

The gearbox bolts to the standard engine mounting face. Oil lines to and from the oil cooler/heat exchanger are connected to the gearbox at the initial equipment set up.

A variety of connectors are available including standard circular type, and advanced flat plug-in connectors with heavy gauge ribbon style cable.

Interconnect cables are run from the HFAs to the mounting tray for interface to the HFAs. This is performed only when the initial configuration of the engine generator set is made.

Table 23. Optimum Cooling and Packaging Arrangements

	POWER RANGE				
	0.5 - 3.0 kW	**5 - 15 kW**	**20 - 60 kW**	**100 - 200 kW**	**500 - 1000 kW**
Power Frequency Converter	– Split Package HFA/PFC – Rack Mounted – Air Cooled	– Modular Design – Split Package HFA/PFC – Rack Mounted – Oil Cooled Cold Plate	– Modular Design – Split Package HFA/PFC – Rack Mounted – Oil Cooled Cold Plate	– Modular Design – Split Package HFA/PFC – Rack Mounted – Oil Cooled Cold Plate	– Modular Design – Split Package HFA/PFC – Rack Mounted – Oil Cooled Cold Plate
High Frequency Alternator	– Split Package HFA/PFC – Bolt Circle Mount – Air Cooled	– Modular Design – Split Package HFA/PFC – Bolt Circle Mount – Oil Cooled – Oil Lubricated	– Modular Design – Split Package HFA/PFC – Bolt Circle Mount – Oil Cooled – Oil Lubricated	– Modular Design – Split Package HFA/PFC – Bolt Circle Mount – Oil Cooled – Oil Lubricated	– Modular Design – Split Package HFA/PFC – Bolt Circle Mount – Oil Cooled – Oil Lubricated
Interface Gearbox	– Stand Alone Unit – Bolt Circle Mount – Oil Lubricated	– Stand Alone Unit – Bolt Circle Mount – Oil Lubricated – Oil Cool – Closed System W/ HFA/PFC	– Stand Alone Unit – Bolt Circle Mount – Oil Lubricated – Oil Cool – Closed System W/ HFA/PFC	– Stand Alone Unit – Bolt Circle Mount – Oil Lubricated – Oil Cool – Closed System W/ HFA/PFC	– Stand Alone Unit – Bolt Circle Mount – Oil Lubricated – Oil Cool – Closed System W/ HFA/PFC
Accessory Modules		– Modular Interface – Rack Mounted	– Modular Interface – Rack Mounted	– Modular Interface – Rack Mounted	– Rack Mounted

4.7.1. ALTERNATE CONFIGURATIONS

Consideration was given to alternative installation configurations. Combining the PFC with the HFA may gain a slight weight improvement due to integrated packaging techniques, reduced oil interconnects, and reduced interconnect wiring. The drawback is locating the electronic equipment is a high vibration environment. This will ultimately reduce reliability as vibration tends to be one of the most severe environmental conditions. The same drawbacks occur with locating the PFC on the gearbox.

Additional cooling methods were reviewed. Air cooled equipment typically exhibited a 50% to 100% weight increase over the comparably oil cooled equipment. Vapor Phase Change cooling provides a more direct means of extracting heat from the equipment and dissipating it to the ambient through an interface surface. However, the HFA equipment would require additional oil lubrication circuits. This would increase net size and weight, and have an additional cost.

The modular packaging concept was found to significantly reduce the number of spare units required for field support of a generator set family. The modular technique is slightly less efficient in overall packaging considerations and adds approximately 13% weight to the HFA-PFC System, the net increase to a generator set is less then 1.5%.

4.7.2. COOLING & PACKAGING CONSIDERATIONS

Cooling presents technical challenges as power levels increase. In general, as the power levels increase, losses increase in proportion to the volume of material. Losses increase proportionally to the cube of the material dimensions. However, heat extraction is relative to the surface area in contact with the cooling medium. The interface surface area for an ideal cooling arrangement only increases by the square of the material dimensions. The cooling efficiency goes down as power levels increase. [10]

5. CONCLUSIONS

The system analysis has shown there is significant potential for weight and size reductions in mobile tactical power generation sources. The following provides a summary of concluding points.

- An 87.2% average weight savings over equivalent power 60 Hz generators may be realized through the use of a high speed HFA-PFC System. This number ranges from 80% to 92% in the 5 to 1000 kW power range. These numbers include all accessories required for operation of the HFA-PFC System.
- An average 46.6% weight savings for the entire generator set is possible. Another 2% may be attributed to eliminating the DC starter for a total of 48.6%.
- High speed generators are required for optimum weight savings in order to push the operating frequency sufficiently high.
- Gearboxes used to provide the speed increase can provide a source of cooling oil to further reduce size and weight of the HFAs and PFCs.
- Starter generator capability is intrinsic to the HFA-PFC design.
- The battery used in the starter generator mode can also supply a time limited uninterrutptible power supply mode. This feature is also intrinsic to the PFC design, requiring little additional design.
- Including the parallel operating capability of the current MEPS in an HFA-PFC System, combined with the PFC control of the output frequency, automatically provides the foundation for parallel operation of PFCs in a modular system configuration.
- A modular HFA-PFC system approach will allow a standard set of equipment to service a range of power levels. This will reduce the components required for support from 3 to 1, for that range of power levels.
- The analysis of modular designs may be applied directly to unique designs for each power level.
- The weight penalty associated with the modular design is estimated at less then 15% of the HFA-PFC total weight, or less the 1.3% of the generator set weight.
- VSCF operating modes will increase engine and HFA life expectancy; reduce fuel consumption, and acoustic and infrared emissions; it may allow increases in the service intervals required for the engines.
- Increasing basic pole count of a fixed low speed (1800 rpm) generator will not provide significant weight savings due to the generator low frequency output and additional PFC input filtering required.
- Reduced life cycle costs are a potential when considering the advantages of VSCF operation and the modular system approach to reduce inventory, spares support, and acquisition costs.
- Future weight reductions may be provided by further growth in power semiconductor capability. Smart systems can incorporate neural networks for load scheduling, and reconfiguration of loads during certain maneuvers.

The analysis and technologies presented are inline with aerospace standards for electric power generation. Some may even be considered on the conservative side.

6. RECOMMENDATIONS

It is recommended that work progress into the design, development and testing stages of a prototype system based upon the significant potential weight savings for electric generator sets using presently available technology.

The prototype system should demonstrate the 20 kW modular HFA-PFC System approach since the weight analysis estimates the largest savings should occur at this power level.

The detailed analysis and design to be undertaken during Phase II should include:

- Specific definitions of design requirements
- Electromagnetic design using computer based numerical computation
- Computer aided numerical thermal analysis
- Computer aided finite element mechanical stress analysis and critical speed analysis
- Computer aided circuit simulations of power converter
- CAD techniques for mechanical packaging and layout.

Additional areas that require attention are:

- Explore the modular system approach
- Evaluate cost impact of the modular system
- Explore potential life cycle cost reduction for MEPS equipment
- Continually evaluate evolving technology for potential benefits

The detailed design should be pursued to demonstrate the potential weight savings projected in this Phase I effort.

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Military Standards, Specifications, and Handbooks:

MIL-HDBK-241B	Military Handbook Design Guide for Electromagnetic Interference Reduction in Power Supplies
MIL-STD-454N	Military Standard Standard General Requirements for Electronic Equipment
MIL-STD-461D	Military Standard Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility
MIL-STD-633E	Military Standard Mobile Electric Power Engine Generator Standard Family General Characteristics
MIL-STD-705C	Military Standard Generator Sets, Engine Driven Methods of Tests and Instructions
MIL-STD-1332B	Military Standard Definitions of Tactical, Prime, Precise, and Utility Terminologies for Classification of the DoD Mobile Electric Power Engine Generator Set Family
MIL-STD-1410A	Military Standard Methods for Selection of Industrial Engines for End Item Application
MIL-STD-1474C	Military Standard Noise Limits for Military Material

8. DISTRIBUTION LIST

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APPENDIXES

Appendix A Standard Family Specifications

Mobile Electric Power Generating Set Characteristics

Data gathered from MIL-STD-633E, Mobile Electric Power Engine Generator Standard Family General Characteristics

			Output	Output	Voltage	Engine					
Model #	kW Rating	Weight	Voltage (V)	Frequency (Hz)	Connection	Type	MTBF	Comments		Type	Class
MEP-014A	0.5	85	120	60	2 wire, 1ϕ	G	250	air cooled, rope start			
MEP-019A	0.5	85	120	400	2 wire, 1ϕ	G	250	air cooled, rope start			
MEP-024A	0.5	85	28	DC	2 wire, DC	G	250	air cooled, rope start			
MEP-015A	1.5	125	120	60	2 wire, 1ϕ	G	250	air cooled, rope start			
			240	60	2 wire, 1ϕ						
MEP-025A	1.5	125	28	DC	2 wire, DC	G	250	air cooled, rope start			
MEP-016A	3	285	120	60	2 wire, 1ϕ	G	250	air cooled, rope start			
			240	60	2 wire, 1ϕ						
			120	60	3 wire, 3ϕ						
			120/208	60	4 wire, 3ϕ						

MEP-021A	3	285	120	400	2 wire, 1ϕ	G	250	air cooled, rope start			
			240	400	2 wire, 1ϕ						
			120	400	3 wire, 3ϕ						
			120/208	400	4 wire, 3ϕ						
MEP-026A	3	285	28	DC	2 wire, DC	G	250	air cooled, rope start			
MEP-017A	5	488	120	60	2 wire, 1ϕ	G	250	air cooled			
			240	60	2 wire, 1ϕ			24 VDC Start			
			120	60	3 wire, 3ϕ			rope start			
			120/208	60	4 wire, 3ϕ						
MEP-002A	5	930	120	60	2 wire, 1ϕ	D	500	air cooled			
			120/240	60	3 wire, 1ϕ			24 VDC electric start			
			120/208	60	4 wire, 3ϕ						
MEP-022A	5	479	120	400	2 wire, 1ϕ	G	250	air cooled			
			240	400	2 wire, 1ϕ			24 VDC Start			
			120	400	3 wire, 3ϕ			rope start			
			120/208	400	4 wire, 3ϕ						

MEP-018A	10	850	120	60	2 wire, 1ϕ	G	250	air cooled				
			120/240	60	3 wire, 1ϕ			24 VDC Start				
			120	60	3 wire, 3ϕ			rope start				
			120/208	60	4 wire, 3ϕ							
MEP-003A	10	1240	120	60	2 wire, 1ϕ	D	500	air cooled				
			120/240	60	3 wire, 1ϕ			24 VDC electric start				
			120/208	60	4 wire, 3ϕ							
MEP-412A	10	456	120	60	2 wire, 1ϕ	GT	750	air cooled				
			120/240	60	3 wire, 1ϕ			24 VDC electric start				
			120/208	60	4 wire, 3ϕ							
MEP-023A	10	650	120	400	2 wire, 1ϕ	G	250	air cooled				
			120/240	400	3 wire, 1ϕ			24 VDC Start				
			120	400	3 wire, 3ϕ			rope start				
			120/208	400	4 wire, 3ϕ							
MEP-112A	10	1325	120	400	2 wire, 1ϕ	D	500	air cooled				
			120/240	400	3 wire, 1ϕ			24 VDC electric start				
			120/208	400	4 wire, 3ϕ							

MEP-414A	10	300	28	DC	2 wire, DC	GT	500	air cooled				
								24 VDC electric start				
MEP-004A	15	2450	120/208	60	4 wire, 3ϕ	D	670	Liquid cooled			Tactical	Utility
			240/416	60	4 wire, 3ϕ			24 VDC electric start				
			120/208	50	4 wire, 3ϕ			Parallel operating capability				
			240/416	50	4 wire, 3ϕ							
MEP-103A	15	2450	120/208	60	4 wire, 3ϕ	D	370	Liquid cooled			Tactical	Precise
			240/416	60	4 wire, 3ϕ			24 VDC electric start				
			120/208	50	4 wire, 3ϕ			Parallel operating capability				
			240/416	50	4 wire, 3ϕ							
MEP-113A	15	2500	120/208	400	4 wire, 3ϕ	D	370	Liquid cooled				Precise
			240/416	400	4 wire, 3ϕ			24 VDC electric start				
								Parallel operating capability				
MEP-005A	30	2850	120/208	60	4 wire, 3ϕ	D	670	Liquid cooled				
			240/416	60	4 wire, 3ϕ			24 VDC electric start				
			120/208	50	4 wire, 3ϕ			Parallel operating capability				
			240/416	50	4 wire, 3ϕ							

MEP-104A	30	2850	120/208	60	4 wire, 3ϕ	D	370	Liquid cooled	Tactical	Precise
			240/416	60	4 wire, 3ϕ			24 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-114A	30	3000	120/208	400	4 wire, 3ϕ	D	370	Liquid cooled	Tactical	Precise
			240/416	400	4 wire, 3ϕ			24 VDC electric start		
								Parallel operating capability		
MEP-006A	60	4240	120/208	60	4 wire, 3ϕ	D	500	Liquid cooled	Tactical	Utility
			240/416	60	4 wire, 3ϕ			24 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-105A	60	4300	120/208	60	4 wire, 3ϕ	D	420	Liquid cooled	Tactical	Precise
			240/416	60	4 wire, 3ϕ			24 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-115A	60	4400	120/208	400	4 wire, 3ϕ	D	450	Liquid cooled	Tactical	Precise
			240/416	400	4 wire, 3ϕ			24 VDC electric start		
								Parallel operating capability		

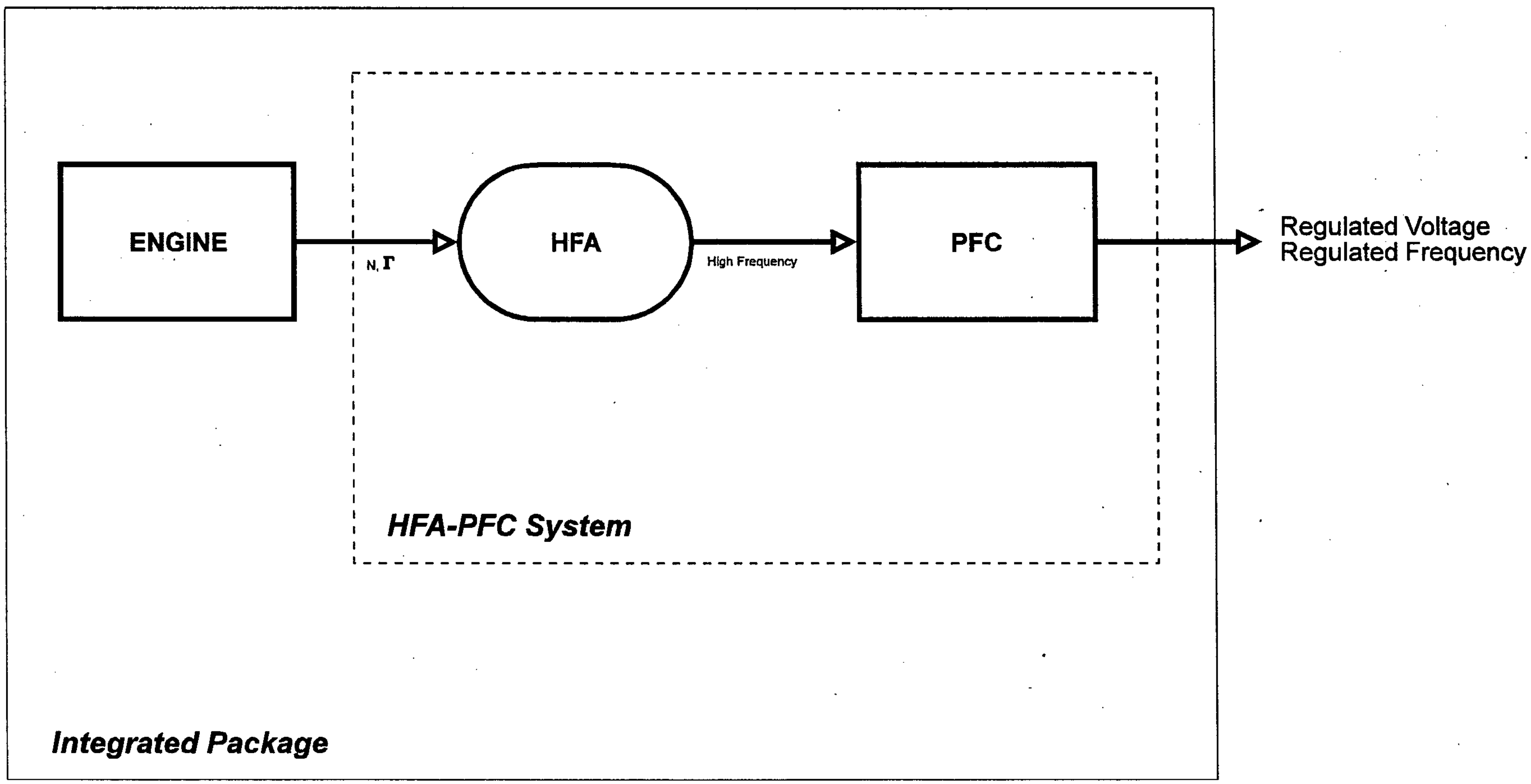
MEP-404A	60	950	120/208	400	4 wire, 3ϕ	GT	1500	Air cooled			Tactical	Precise
			240/416	400	4 wire, 3ϕ			24 VDC electric start				
								Parallel operating capability				
MEP-356A	60	2800	115/200	400	4 wire, 3ϕ	GT	478	Trailer mounted			Tactical	Precise
			28	DC	2 wire, DC			Electric self propelled				
								Aircraft ground support power unit				
								Air cooled				
								24 VDC electric start				
MEP-357A	72	7000	115/200	400	4 wire, 3ϕ	D	250	Trailer mounted				
			28	DC	2 wire, DC			Aircraft ground support power unit				
								Liquid cooled				
								24 VDC electric start				
MEP-007B	100	7000	120/208	60	4 wire, 3ϕ	D	580	Liquid cooled				
			240/416	60	4 wire, 3ϕ			24 VDC electric start				
			120/208	50	4 wire, 3ϕ			Parallel operating capability				
			240/416	50	4 wire, 3ϕ							
MEP-116B	100	7000	120/208	400	4 wire, 3ϕ	D	580	Liquid cooled				
			240/416	400	4 wire, 3ϕ			24 VDC electric start				
								Parallel operating capability				

MEP-009B	200	10500	120/208	60	4 wire, 3ϕ	D	468	Liquid cooled		
			240/416	60	4 wire, 3ϕ			24 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-011A	500	36000	120/208	60	4 wire, 3ϕ	D	500	Liquid cooled	Tactical	Utility
			240/416	60	4 wire, 3ϕ			32 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-029	500	34050	120/208	60	4 wire, 3ϕ	D	500	Liquid cooled	Tactical	Utility
			240/416	60	4 wire, 3ϕ			24 VDC electric start		
			120/208	50	4 wire, 3ϕ			Parallel operating capability		
			240/416	50	4 wire, 3ϕ					
MEP-208A	750	40000	2400/4160	60	4 wire, 3ϕ	D	1200	Liquid Cooled	Prime	Utility
			2400	60	3 wire, 3ϕ			Compressed air starting system		
			2200/3800	50	4 wire, 3ϕ			Parallel operation capability		
			2200	50	3 wire, 3ϕ			Gas engine & electric motor for		
								engine start		
MEP-409A	750	36400	2400/4160	60	4 wire, 3ϕ	GT	1500	24 VDC electric start	Prime	Utility
			2400	60	3 wire, 3ϕ			Housed in van type semi-trailer		
			2000/3460	50	4 wire, 3ϕ			Parallel operation capability		
			2000	50	3 wire, 3ϕ					

Appendix B HFA-PFC System Architecture Block Diagrams

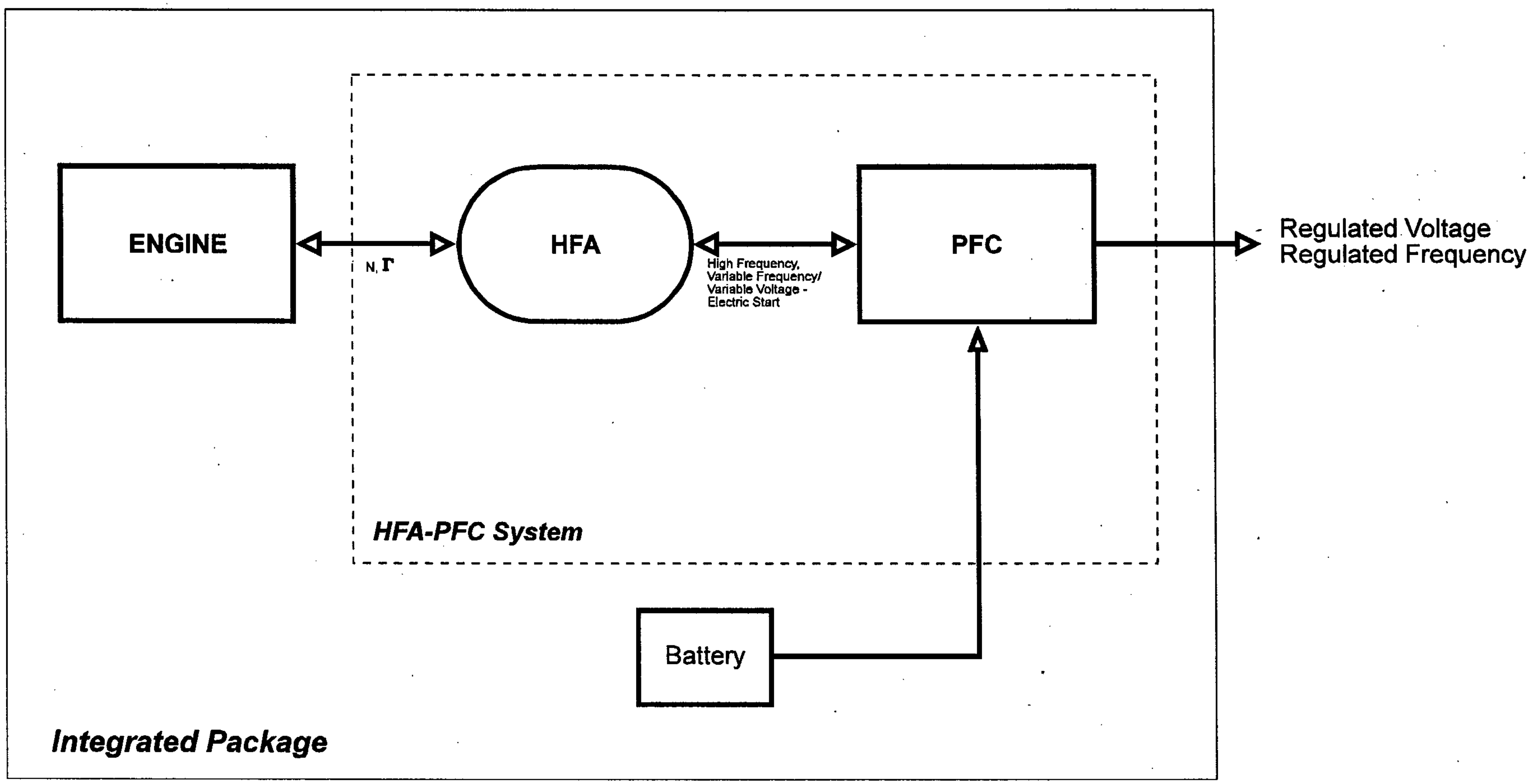
HFA-PFC ARCHITECTURE #: SYS-1

HFA-PFC - SINGLE FUNCTION, INTEGRATED GENERATION AND CONDITIONING (HFA-PFC)



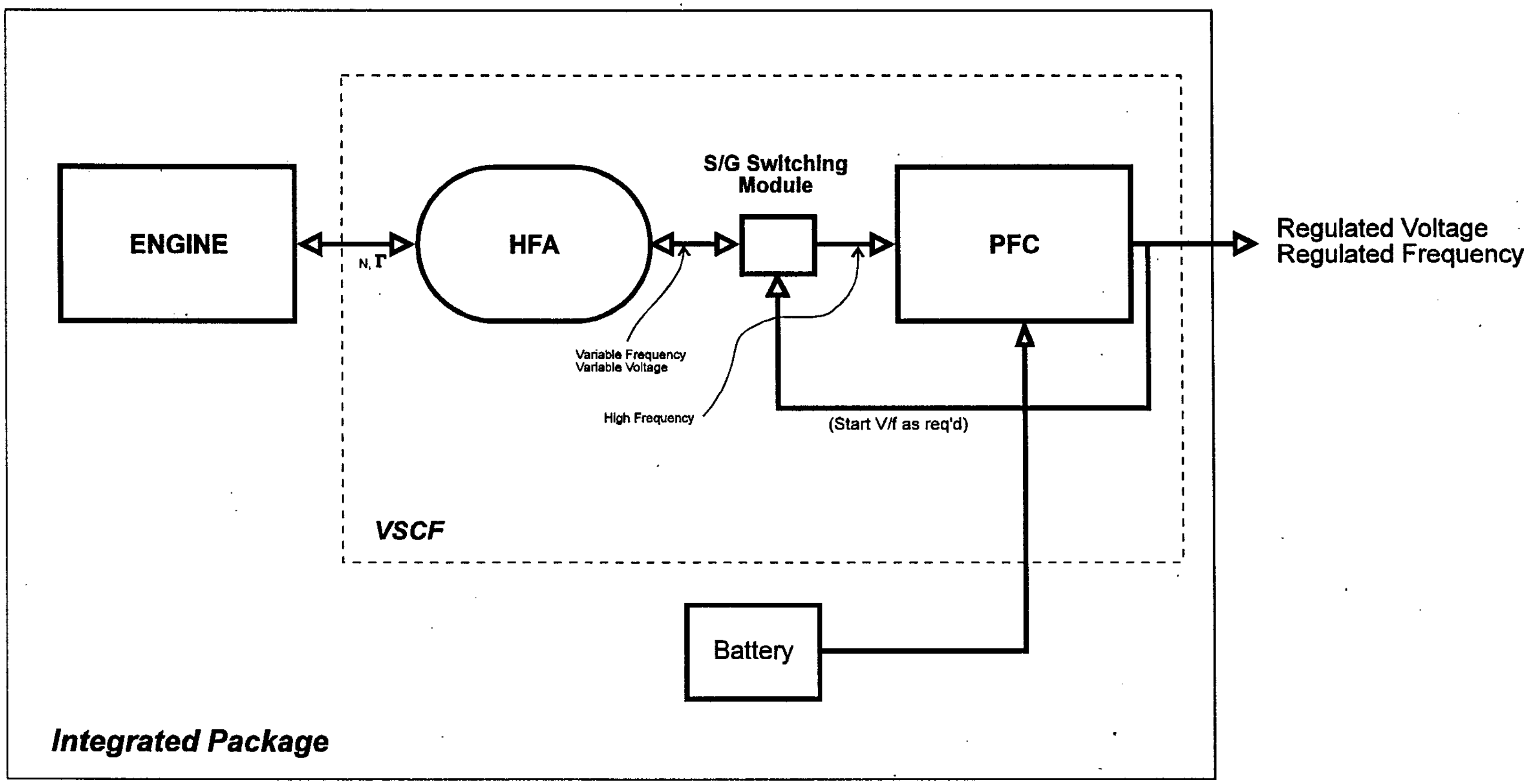
HFA-PFC ARCHITECTURE #: SYS-2

HFA-PFC / Starter-Generator



HFA-PFC ARCHITECTURE #: SYS-2a

HFA-PFC / Starter-Generator (Option)



This configuration is for use with modular architectures. A S/G switching Module is selected based upon the power rating of the engine.

This option may also be offered as an optional configuration on the baseline HFA-PFC single function architecture. The basic configuration is applicable with synchronous wound rotor or permanent magnet machines.

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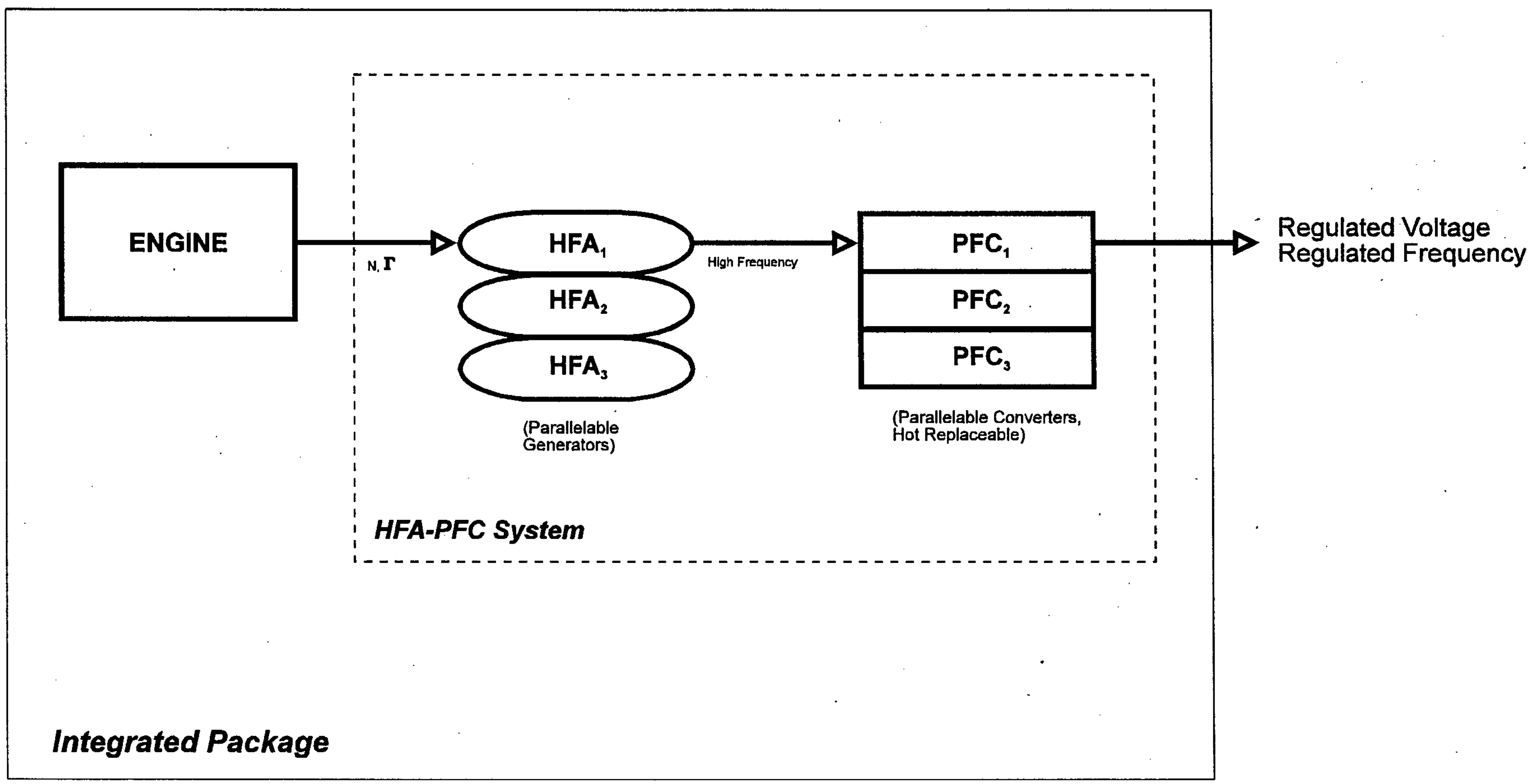
8-30-95

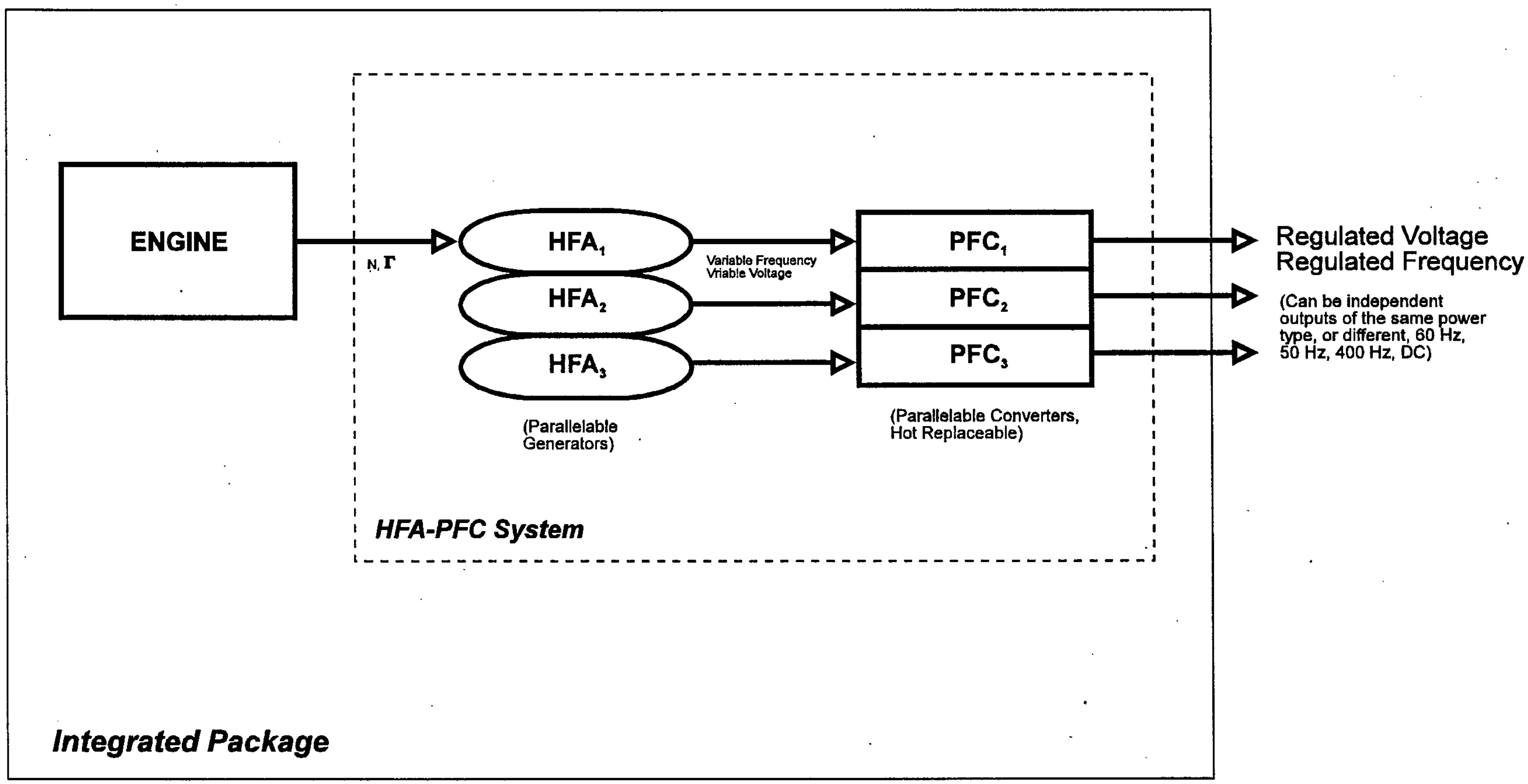
HFA-PFC ARCHITECTURE #: SYS-3

Modular System Architecture



HFA-PFC ARCHITECTURE #: SYS-3a

Modular System Architecture
(Option)



Maximum number of paralleled units will match engine power rating.
S/ al part of each PFC and its outputs will be paralleled.

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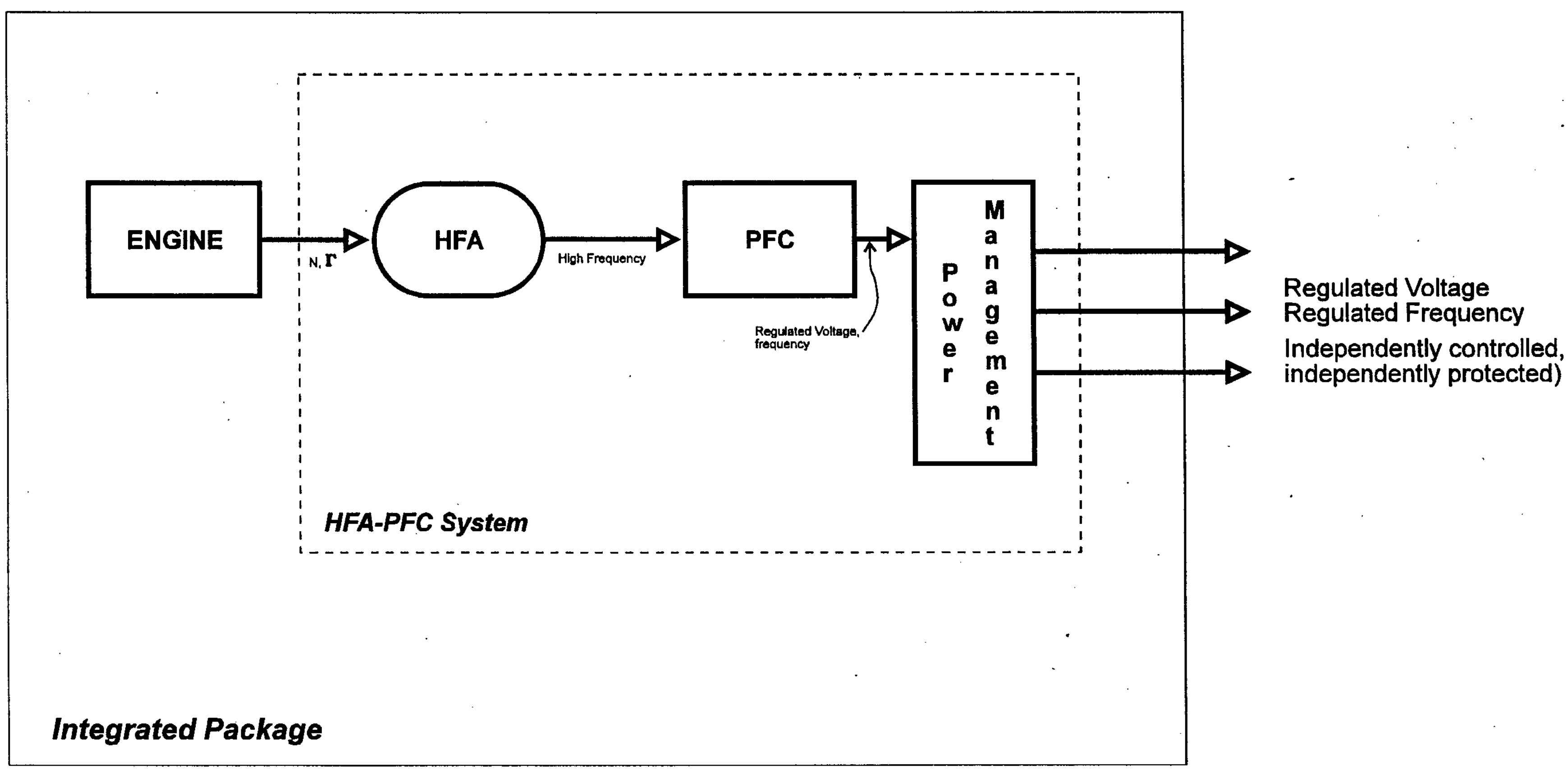
8-30-95

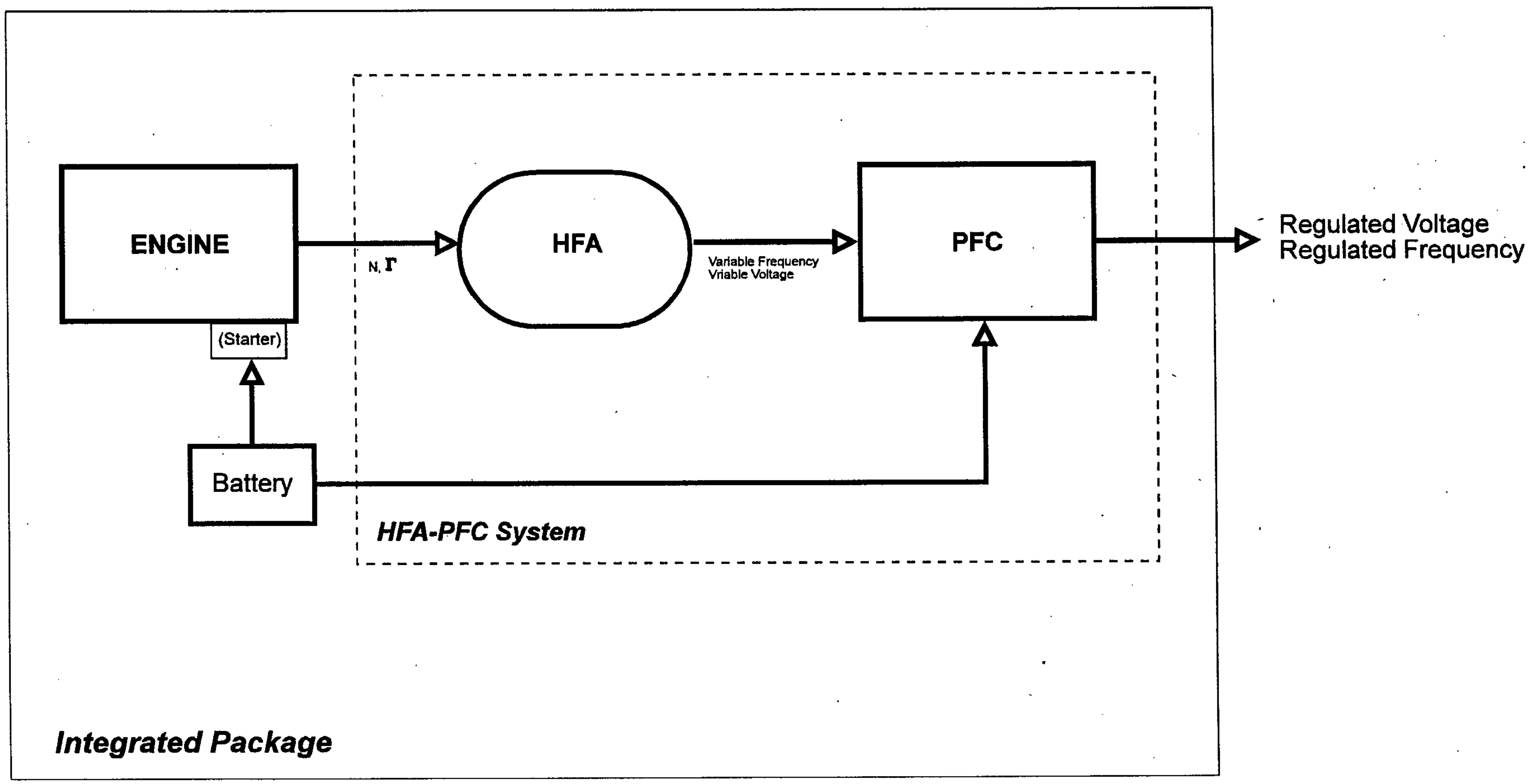
HFA-PFC ARCHITECTURE #: SYS-4

Power Management



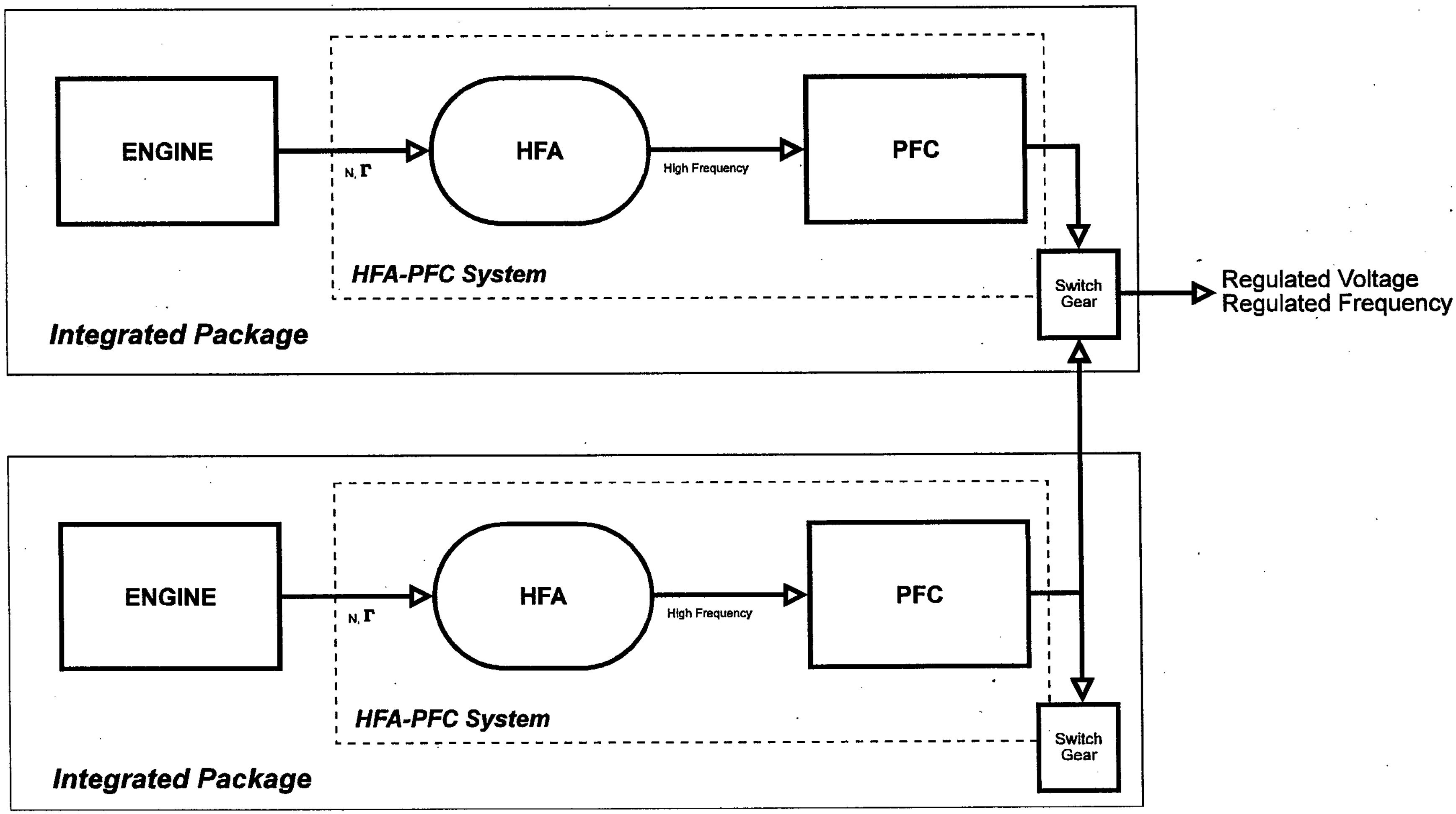
HFA-PFC ARCHITECTURE #: SYS-5

Uninterruptible Power Source (UPS)



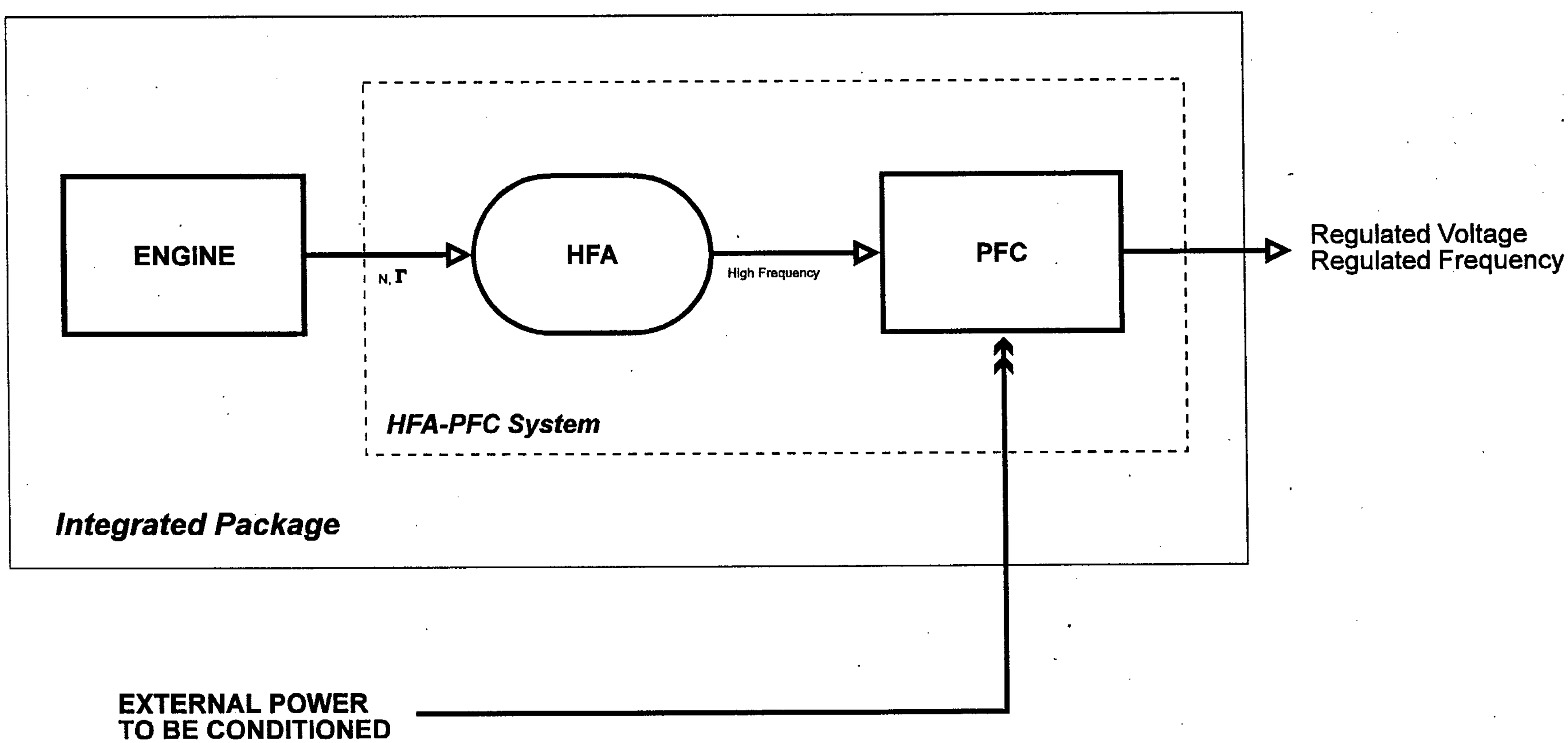
HFA-PFC ARCHITECTURE #: SYS-6

Noninterruptible Power Source



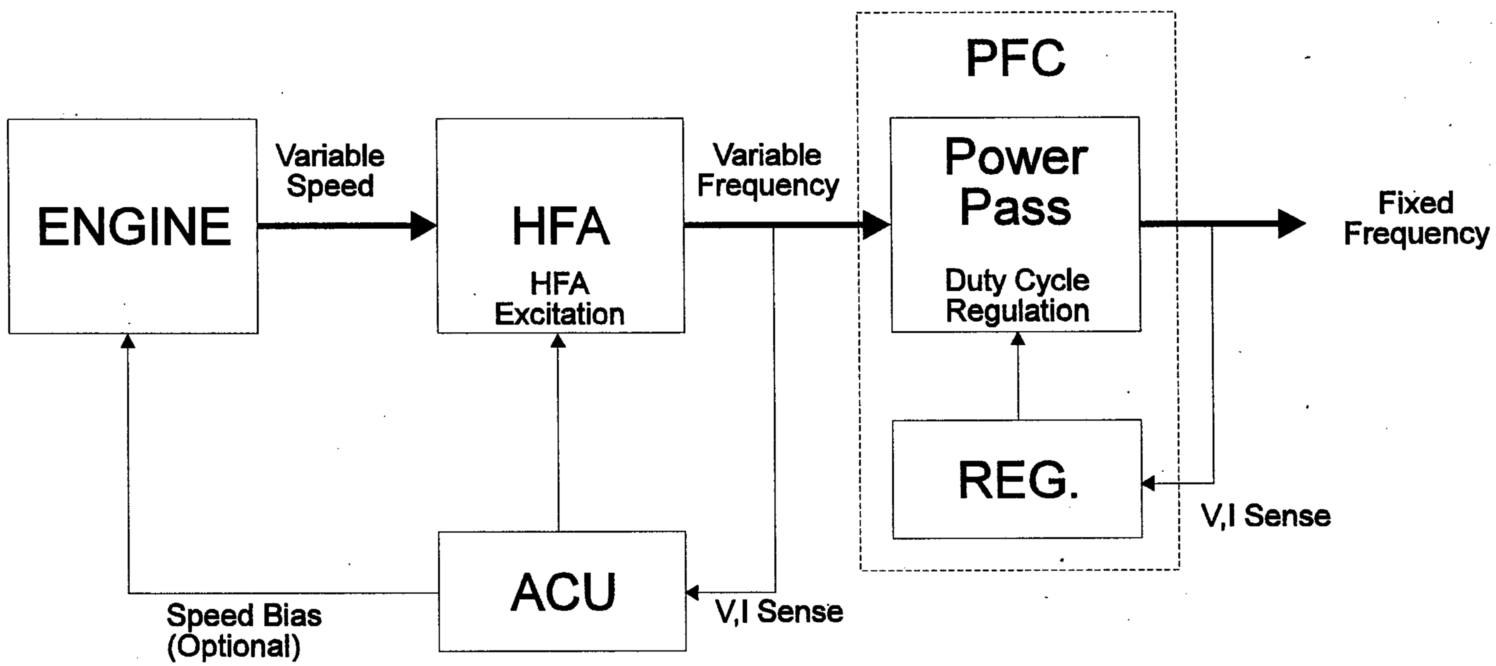
HFA-PFC ARCHITECTURE #: SYS-7

Power Conditioning



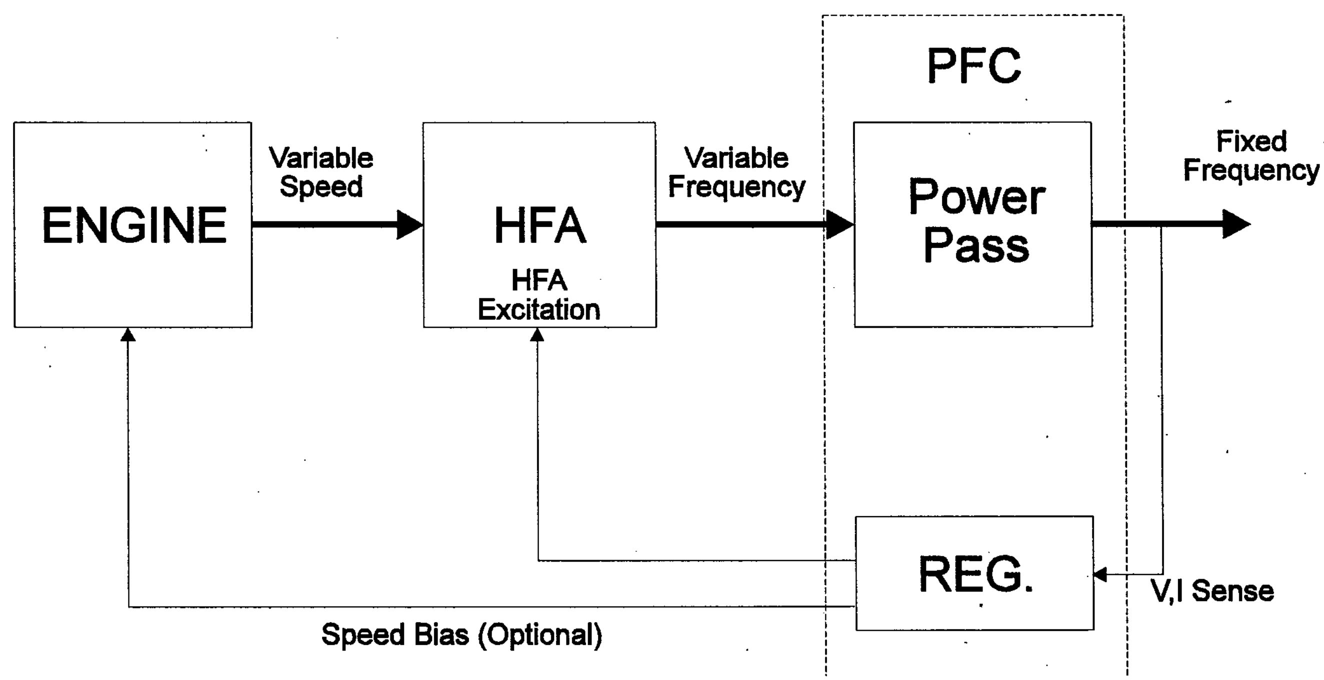
HFA-PFC ARCHITECTURE #: SYS-8

HFA/PFC Independent Regulation



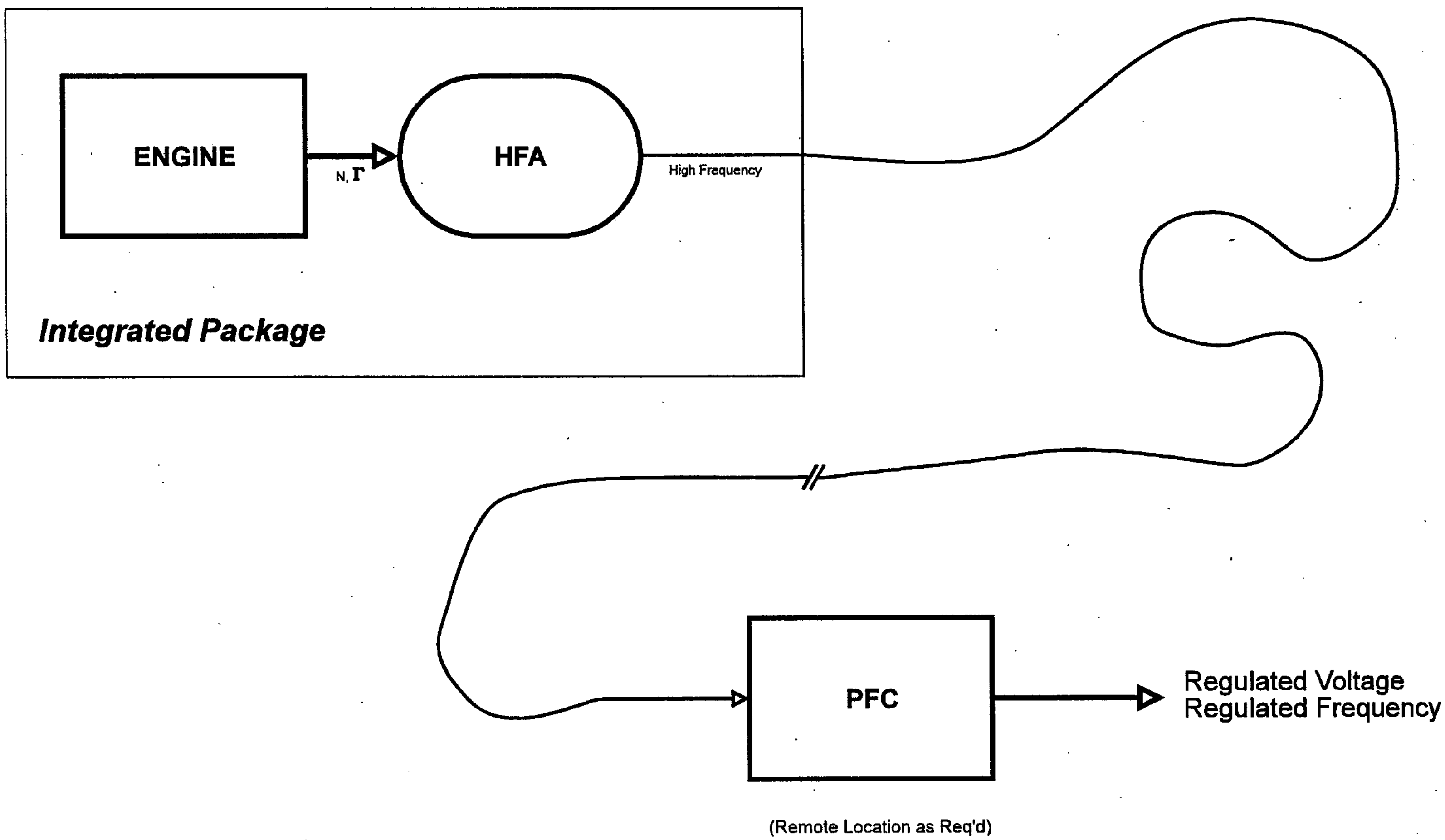
HFA-PFC ARCHITECTURE #: SYS-9

HFA/PFC Coordinated Regulation



HFA-PFC ARCHITECTURE #: SYS-10

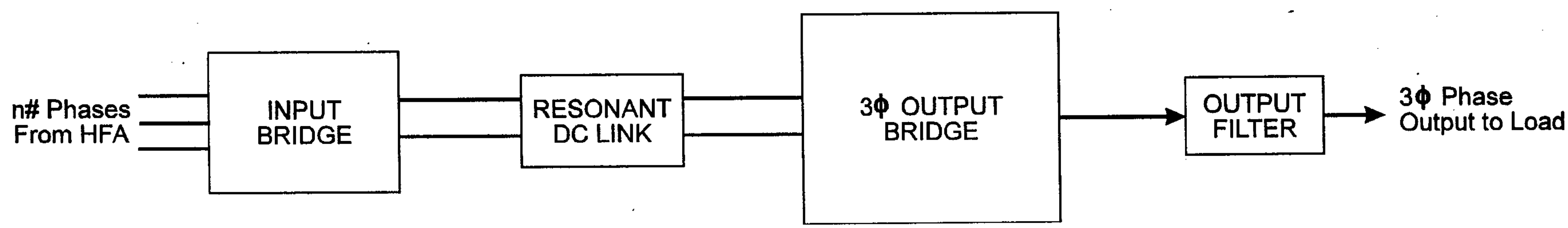
Remote Power Generation / Localized Power Conversion



Appendix C PFC Functional Block Diagrams

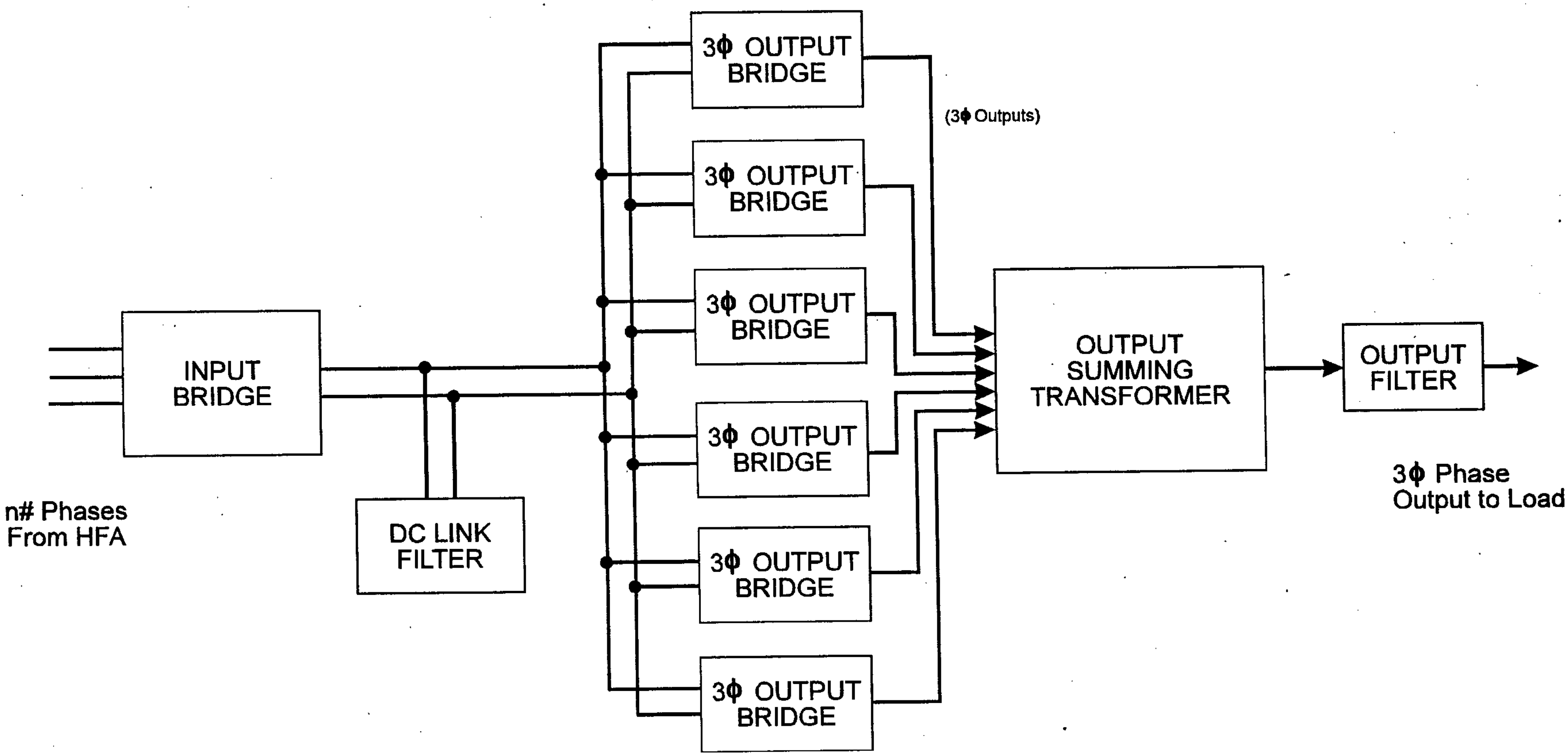
3ϕ PFC TOPOLOGY #: PFC-1

Resonant DC Link



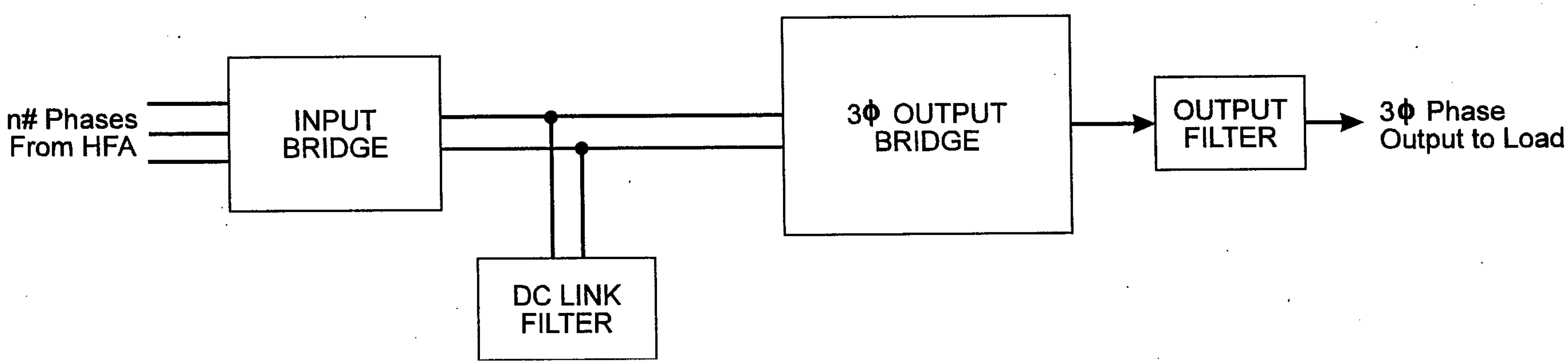
3ϕ PFC TOPOLOGY #: PFC-2

Stepped Waveform / Summing Transformer



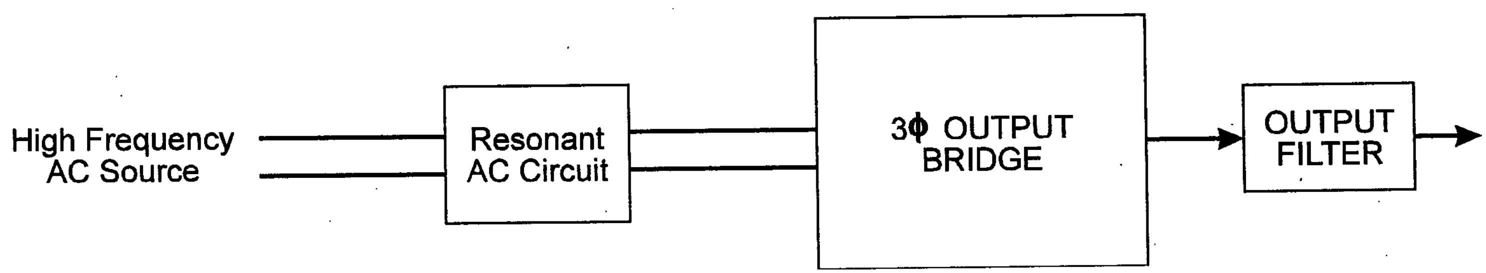
3Φ PFC TOPOLOGY #: PFC-3

Pulse Width Modulation



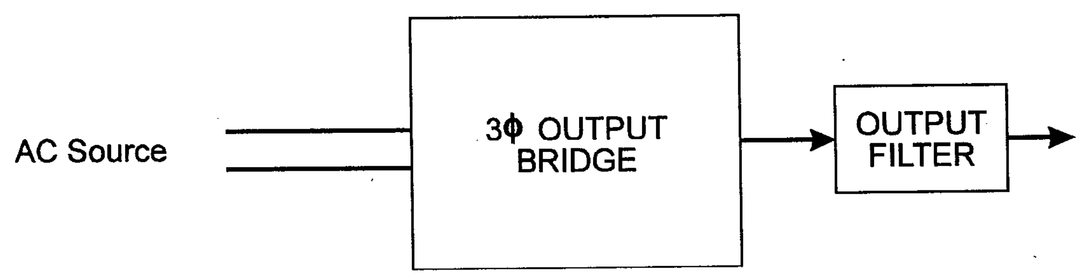
3ϕ PFC TOPOLOGY #: PFC-4

3ϕ High Frequency Link
(AC Link Inverter)



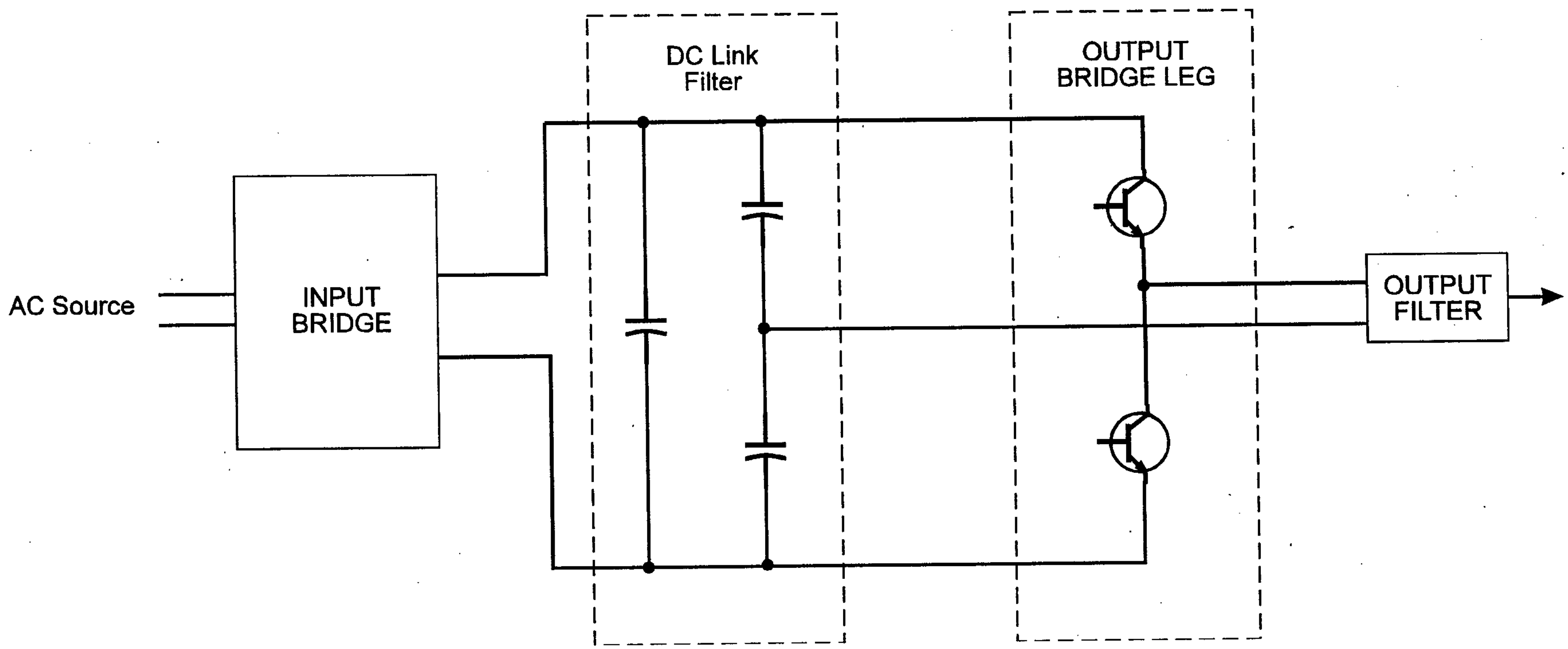
3ϕ PFC TOPOLOGY #: PFC-5

Cycloconverter



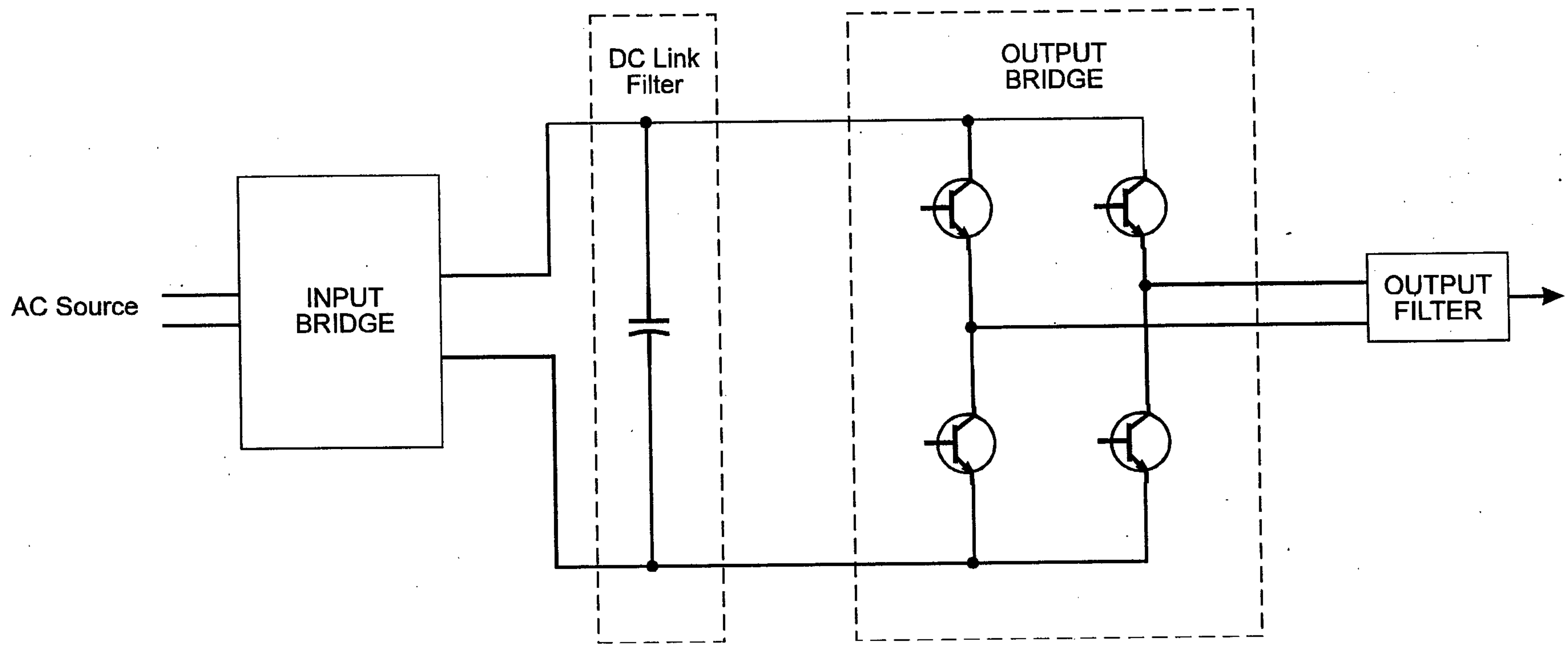
1ϕ PFC TOPOLOGY #: PFC-6

Half Bridge



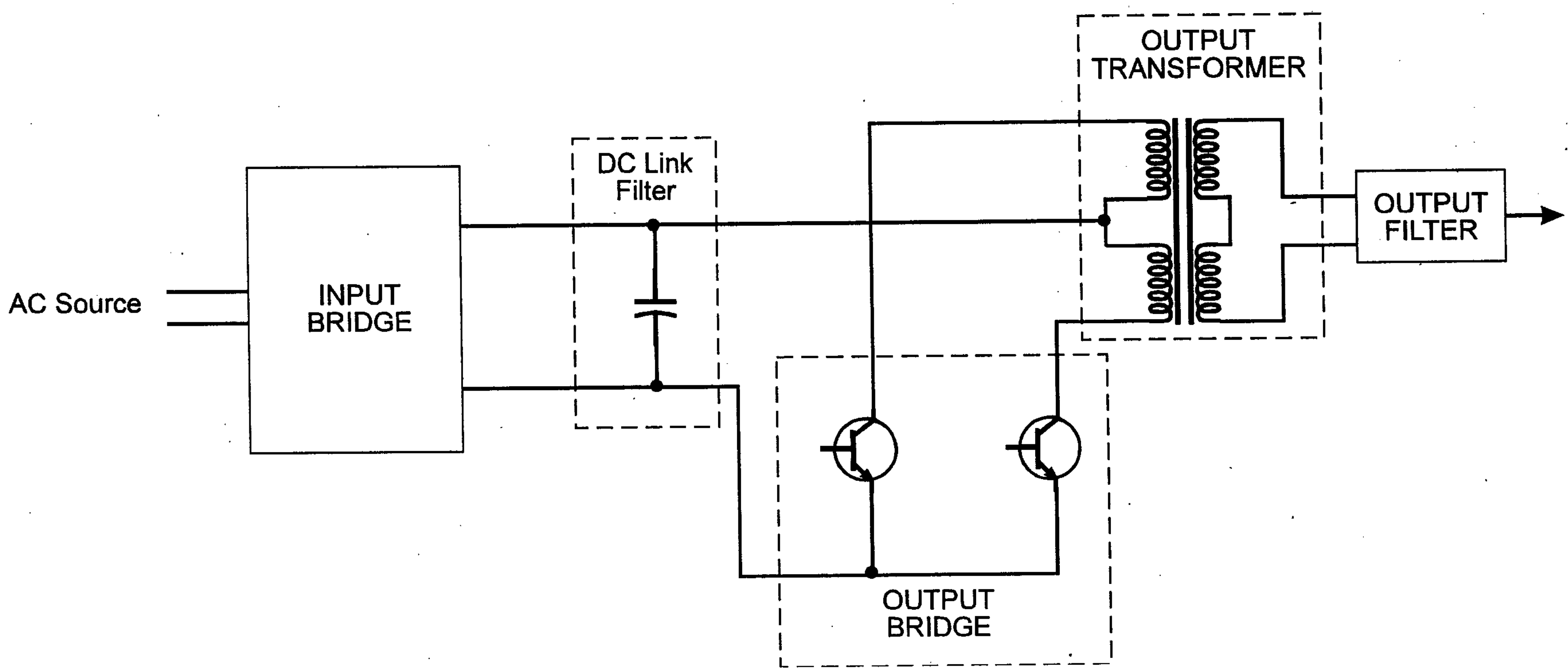
1ϕ PFC TOPOLOGY #: PFC-7

Full Bridge



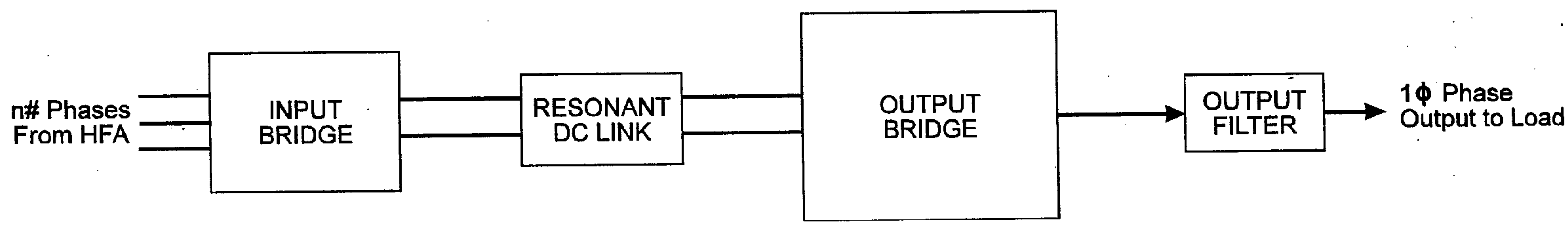
1ϕ PFC TOPOLOGY #: PFC-8

Push Pull Inverter



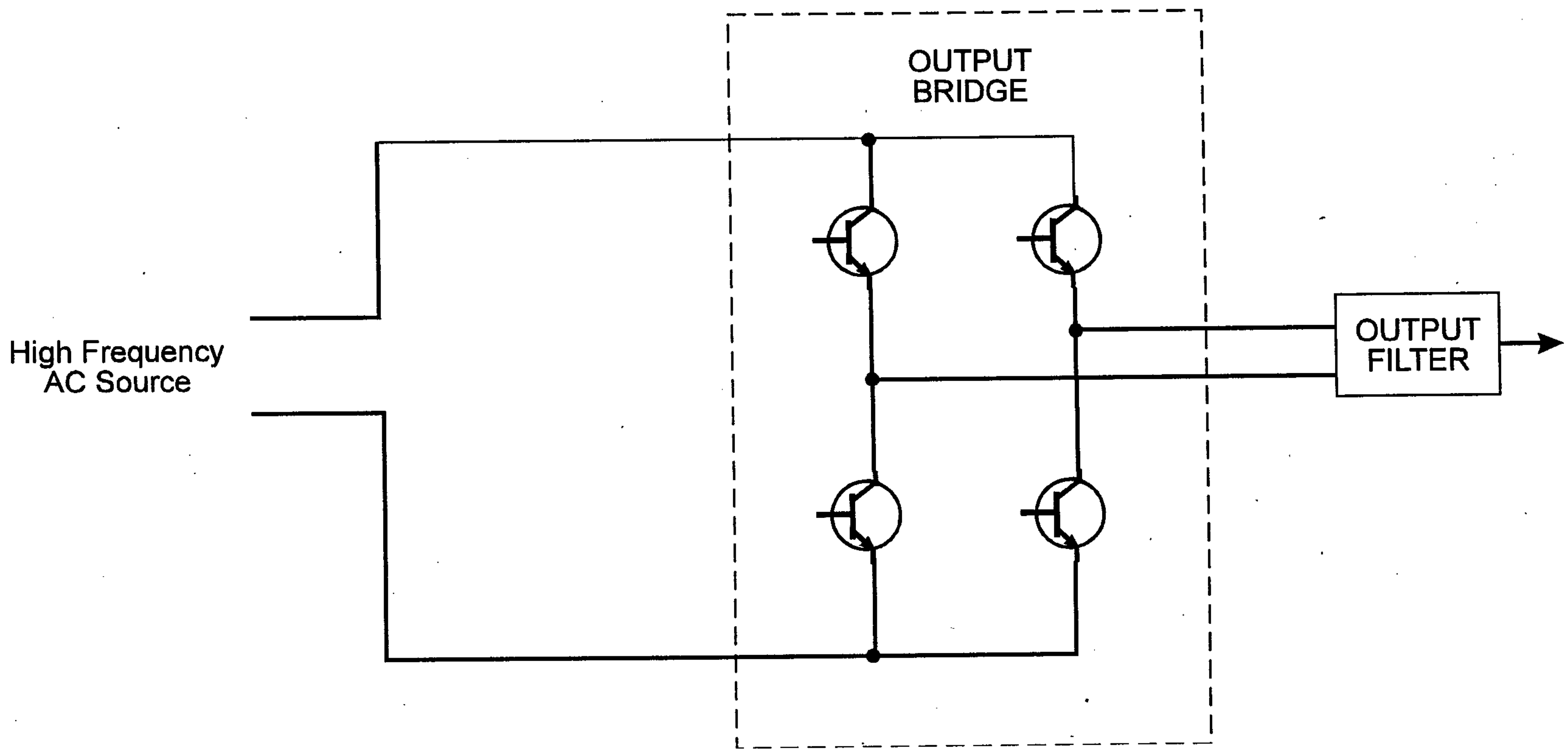
1ϕ PFC TOPOLOGY #: PFC-9

Resonant DC Link



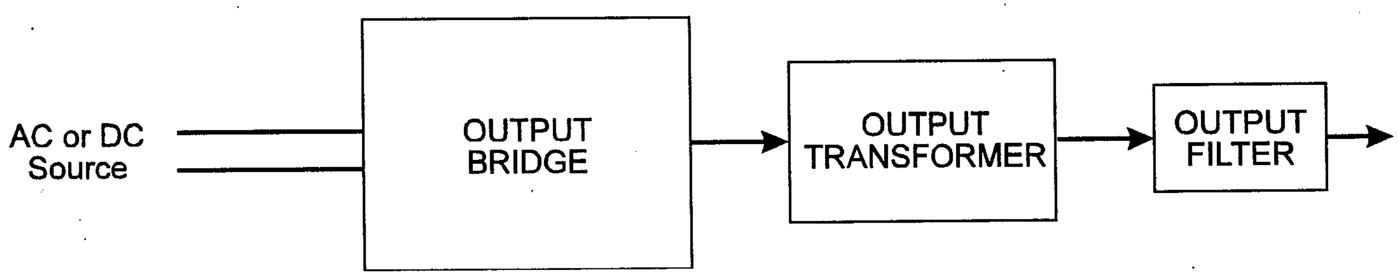
1φ PFC TOPOLOGY #: PFC-10

High Frequency Link



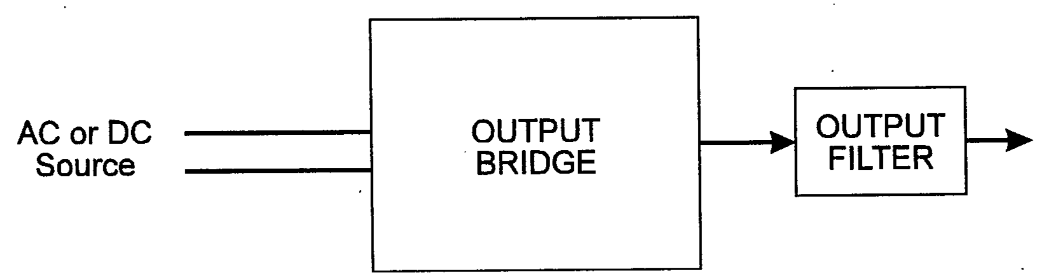
GENERAL PFC TOPOLOGY #: PFC-11

Transformer Coupled Output



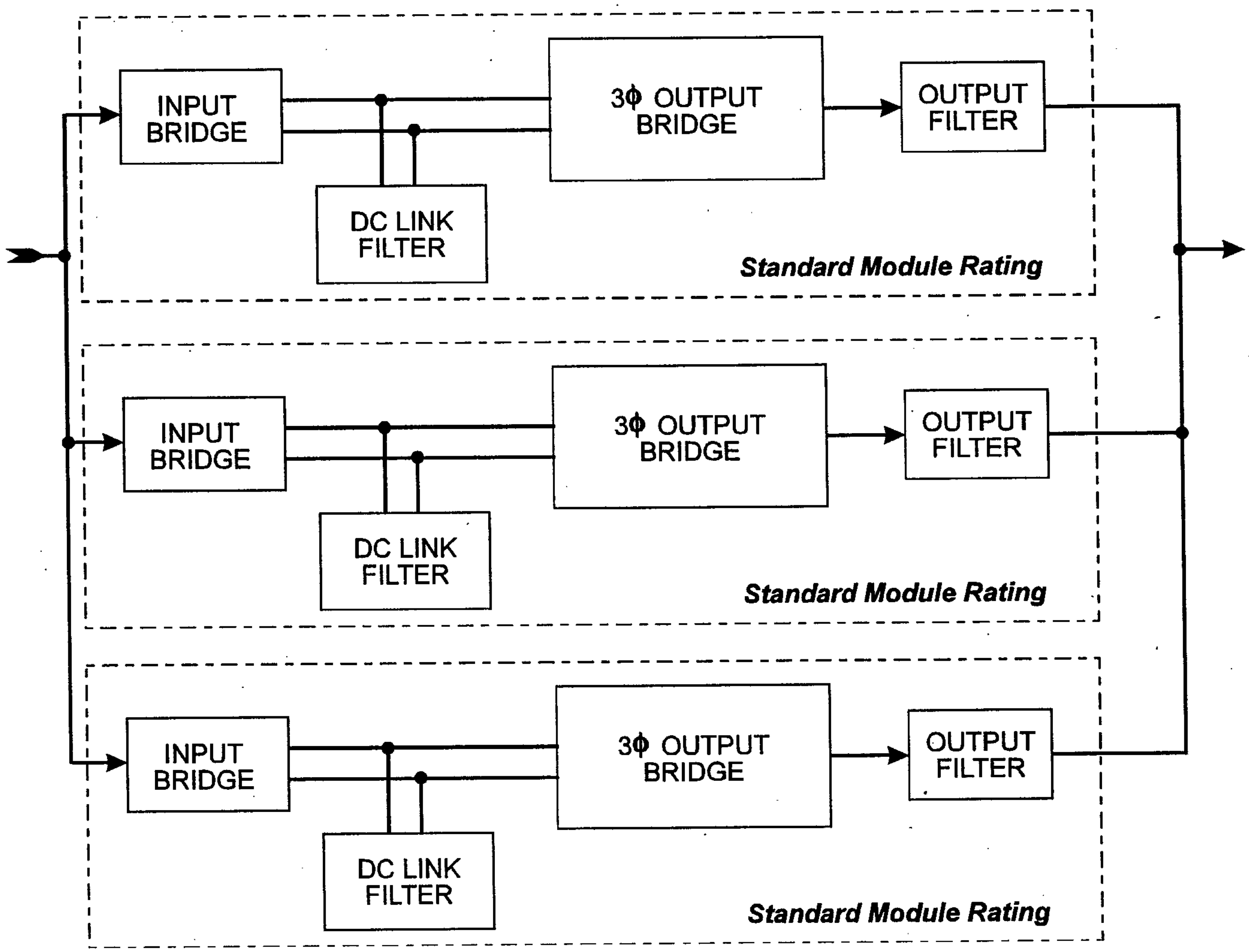
GENERAL PFC TOPOLOGY #: PFC-12

Direct Converter Output



PFC TOPOLOGY #: PFC-13

Modular Topology



Appendix D PFC Power Switch Operating Characteristics

This sheet contains the output power ratings of the HFA-PFC System

	POWER LEVEL(kW)												
	0.5	**1.5**	**3**	**5**	**10**	**15**	**20**	**40**	**60**	**100**	**200**	**500**	**1000**
Summing Transformer	500.0E+0	1.5E+3	3.0E+3	5.0E+3	10.0E+3	15.0E+3	20.0E+3	40.0E+3	60.0E+3	100.0E+3	200.0E+3	500.0E+3	1.0E+6
PWM	500.0E+0	1.5E+3	3.0E+3	5.0E+3	10.0E+3	15.0E+3	20.0E+3	40.0E+3	60.0E+3	100.0E+3	200.0E+3	500.0E+3	1.0E+6
Resonant Link	500.0E+0	1.5E+3	3.0E+3	5.0E+3	10.0E+3	15.0E+3	20.0E+3	40.0E+3	60.0E+3	100.0E+3	200.0E+3	500.0E+3	1.0E+6

Power is in watts

	PFC Output Line-Neutral Voltages (RMS)												
	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Summing Transformer	120	240	240	240	240	240	240	240	240	240	240	2400	2400
PWM	120	240	240	240	240	240	240	240	240	240	240	2400	2400
Resonant Link	120	240	240	240	240	240	240	240	240	240	240	2400	2400
Line to Neutral Voltages (Peak)													
	169.7	339.4	339.4	339.4	339.4	339.4	339.4	339.4	339.4	339.4	339.4	3394.1	3394.1
Line to Line voltages (RMS)													
		415.7	415.7	415.7	415.7	415.7	415.7	415.7	415.7	415.7	415.7	4156.9	4156.9

	PFC Output line currents (RMS)												
	POWER LEVEL (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Summing Transformer	4.2	2.1	4.2	6.9	13.9	20.8	27.8	55.6	83.3	138.9	277.8	69.4	138.9
PWM	4.2	2.1	4.2	6.9	13.9	20.8	27.8	55.6	83.3	138.9	277.8	69.4	138.9
Resonant Link	4.2	2.1	4.2	6.9	13.9	20.8	27.8	55.6	83.3	138.9	277.8	69.4	138.9
Peak Line Currents													
	5.9	2.9	5.9	9.8	19.6	29.5	39.3	78.6	117.9	196.4	392.8	98.2	196.4

Currents are in amperes

Average DC Link Voltage for each topology vs. power range

	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Summing Transformer				543.6	543.6	543.6	543.6	543.6	543.6	543.6	543.6	543.6	543.6
PWM	291.9	711.2	711.2	711.2	711.2	711.2	711.2	711.2	711.2	711.2	711.2	7112.4	7112.4
Resonant Link													
Gen out (AVG)	291.9	754.7	754.7	754.7	754.7	754.7	754.7	754.7	754.7	754.7	754.7	7547.1	7547.1
(peak)	583.8	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	15094.1	15094.1
(peak with voltage clamp approx)	379.5	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	9811.2	9811.2

Avaerage DC Link Current (Amperes)

	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Summing Transformer				9.5	19.0	28.4	37.9	75.9	113.8	189.6	379.3	948.2	1896.5
PWM	1.8	2.2	4.3	7.2	14.5	21.7	29.0	58.0	87.0	144.9	289.9	72.5	144.9
Resonant Link	1.8	2.0	4.1	6.8	13.7	20.5	27.3	54.6	82.0	136.6	273.2	68.3	136.6

Current is in amperes

Review of Resonant DC Link Power Semiconductor Operating Characteristics

	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Resonant Link Current (A)	12.5	6.3	12.5	20.8	41.7	62.5	83.3	166.7	250.0	416.7	833.3	208.3	416.7
Resonant Link Voltage													
Peak (V)	583.8	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	1509.4	15094.1	15094.1
Peak with active clamp (V)	379.5	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	981.1	9811.2	9811.2

Peak Transistor Current for each Topology if used throughout power ranges in high voltage output mode

	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
Summing Transformer				1.6	3.3	4.9	6.5	13.1	19.6	32.7	65.5	160.6	321.2
PWM	7.4	3.7	7.4	12.3	24.6	36.8	49.1	98.2	147.3	245.5	491.0	122.8	245.5
Resonant Link	8.8	4.4	8.8	14.7	29.5	44.2	58.9	117.9	176.8	294.6	589.3	147.3	294.6

Current is in amperes

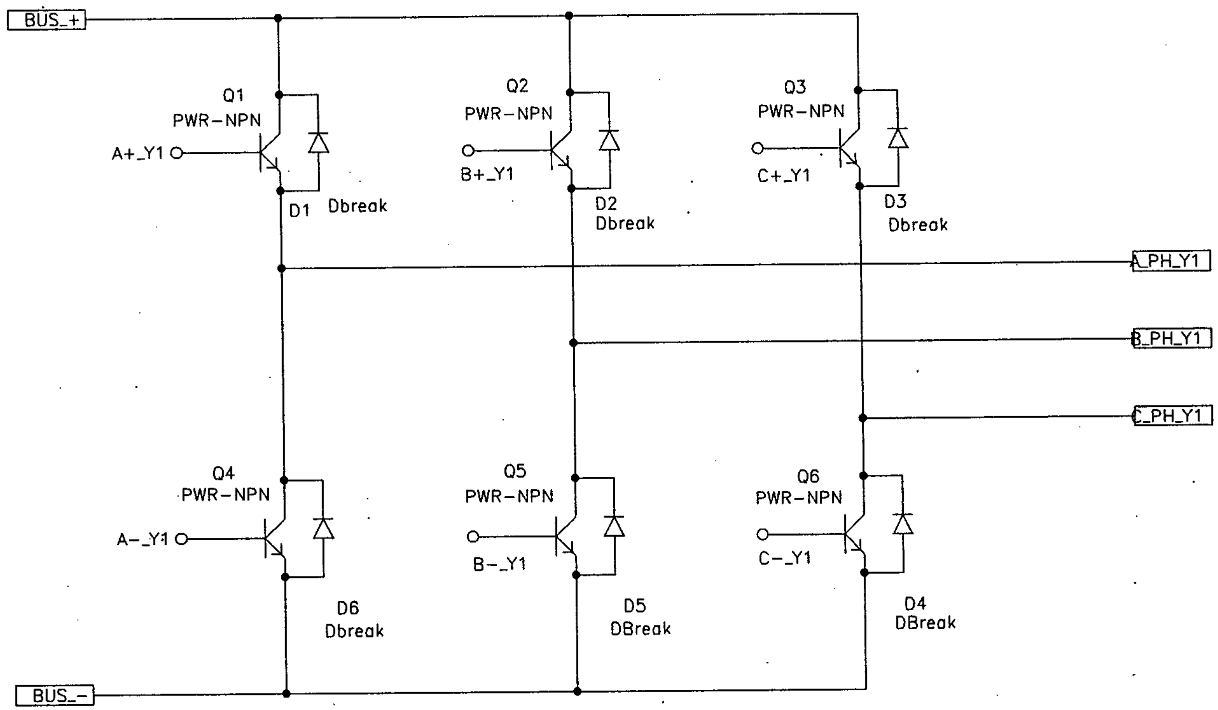
Output Voltages - line to neutral (low voltage connection)

	POWER LEVELS (kW)												
	0.5	***1.5***	***3***	***5***	***10***	***15***	***20***	***40***	***60***	***100***	***200***	***500***	***1000***
V(RMS)	120	120	120	120	120	120	120	120	120	120	120		
Output Currents (phase)													
RMS	4.2	4.2	8.3	13.9	27.8	41.7	55.6	111.1	166.7	277.8	555.6		
Peak	5.9	5.9	11.8	19.6	39.3	58.9	78.6	157.1	235.7	392.8	785.7		
Transistor Peak Currents													
Summing Transformer				1.6	3.3	4.9	6.5	13.1	19.6	32.7	65.5		
PWM	7.4	7.4	14.7	24.6	49.1	73.7	98.2	196.4	294.6	491.0	982.1		
Resonant Link	8.8	8.8	17.7	29.5	58.9	88.4	117.9	235.7	353.6	589.3	1178.5		

Current is in amperes

Appendix E PSPICE Circuit Simulation Results

6 - Bridge Converter Schematics



Six output bridge configuration

This circuit file was established as baseline architecture for HFA-PFC

This circuit is transformer coupled with three each 3 ph wye - delta

Filtered output

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3 PHASE OUTPUT BRIDGE WYE 1	
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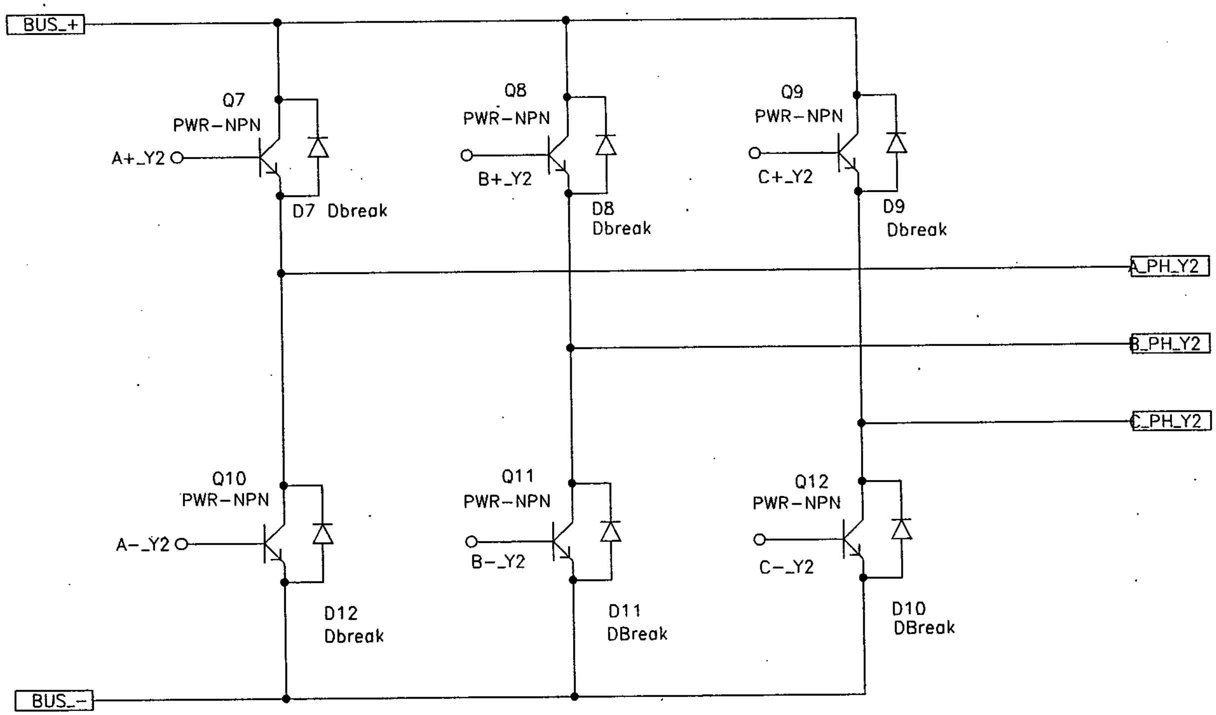

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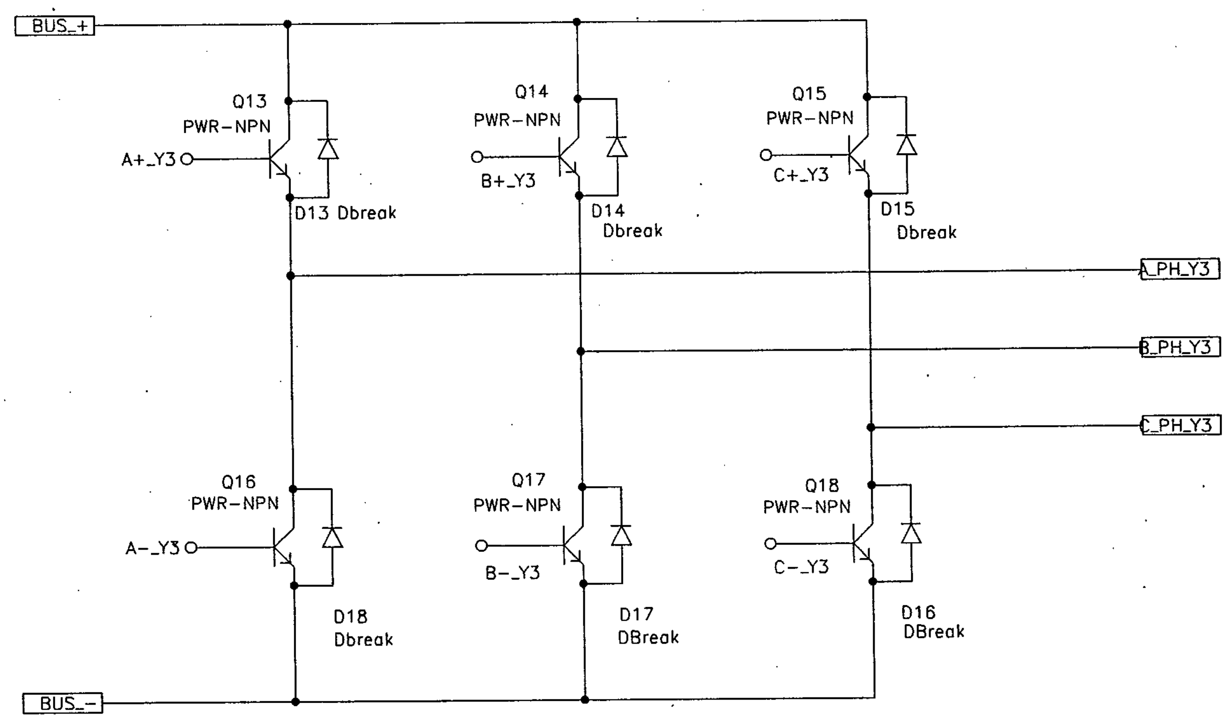

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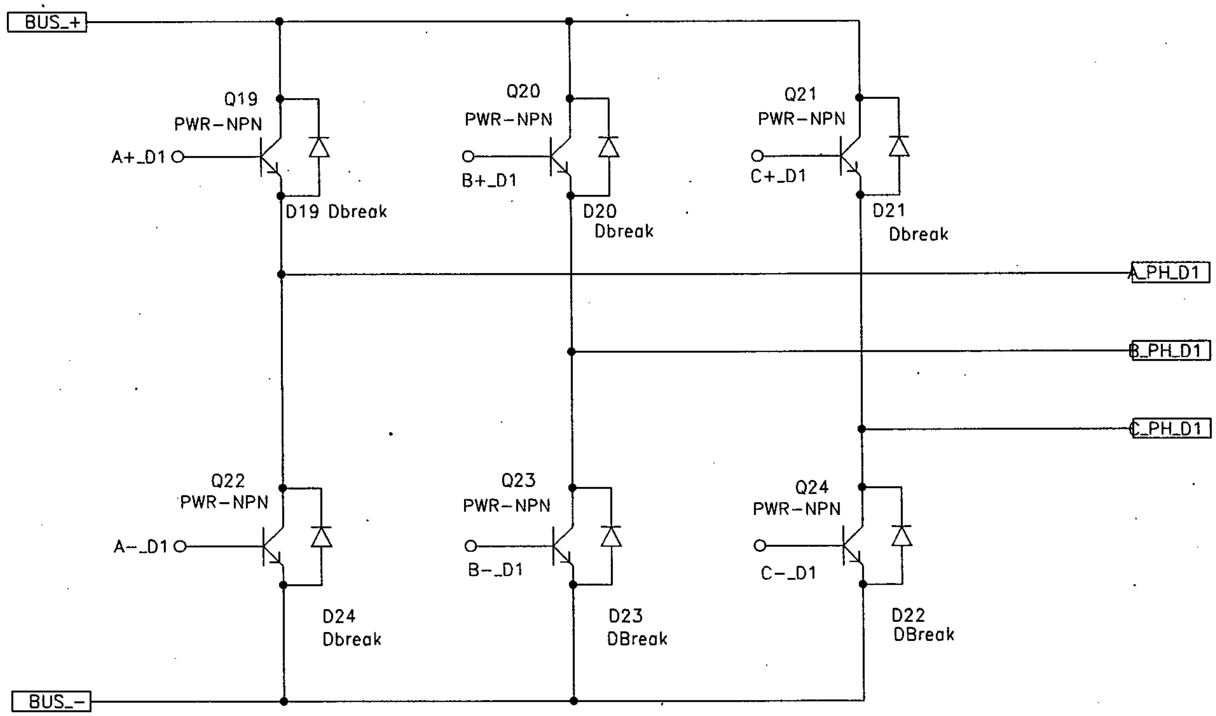

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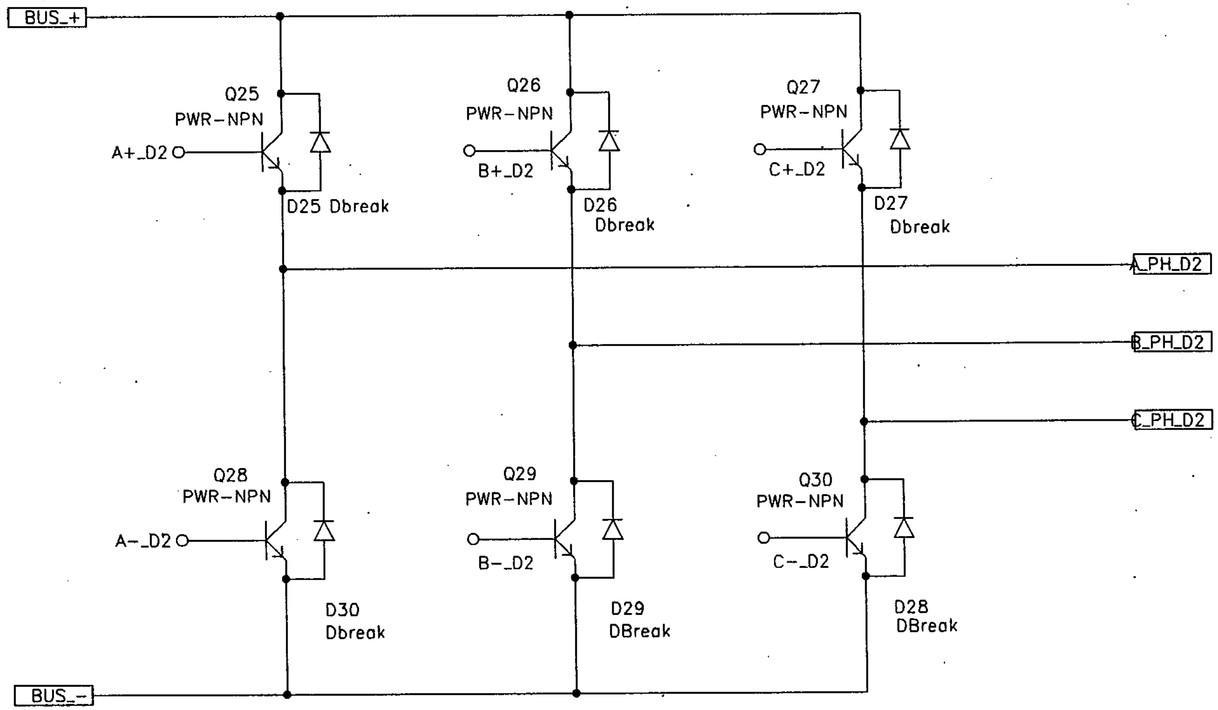

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3 PHASE OUTPUT BRIDGE DELTA 2

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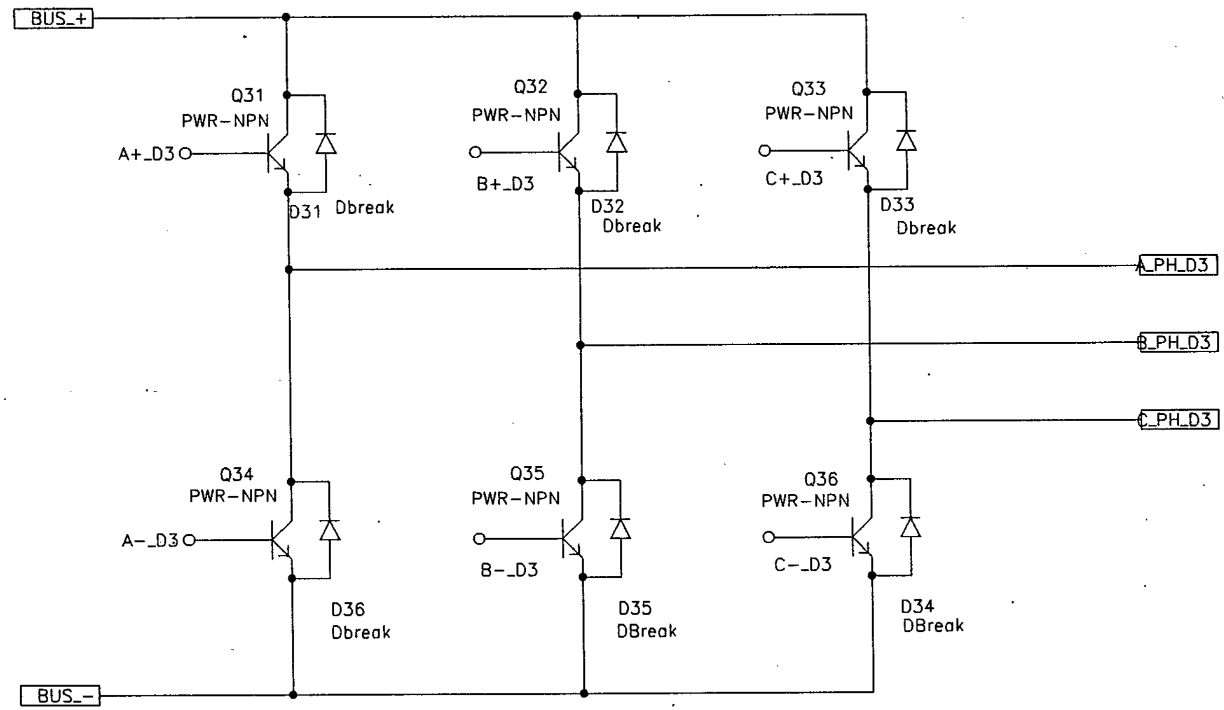

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3 PHASE OUTPUT BRIDGE DELTA 3

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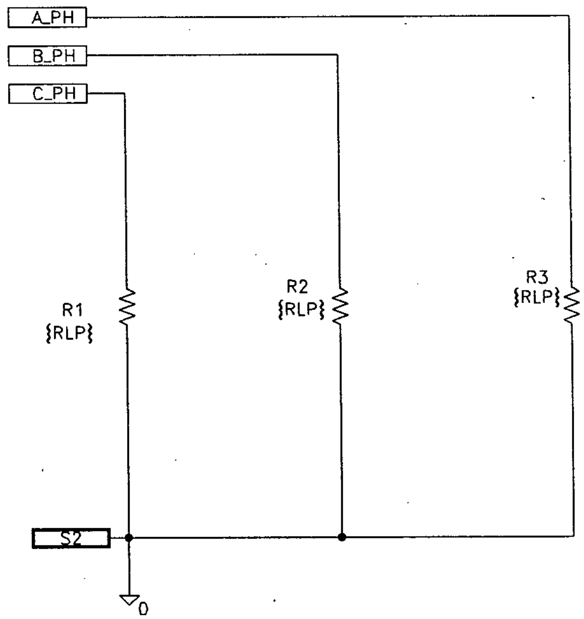

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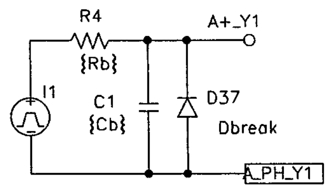

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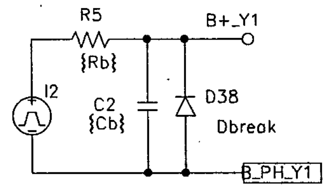

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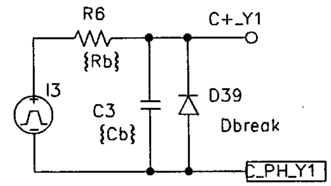

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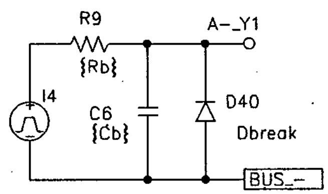

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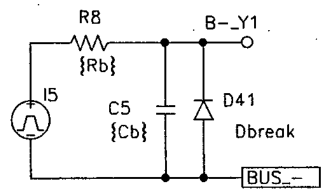

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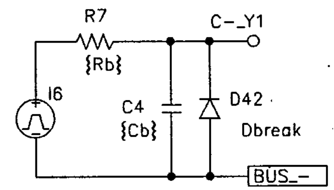

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TR_TF	2us
TPER	{1/60}

PARAMETERS:

PWon	{(TPER/2)−Tdwell−TR_TF}
PWoff	{(TPER/2)−TR_TF}

PARAMETERS:

Rb	5
Cb	0.1uf

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BASE DRIVE SIGNALS WYE 1

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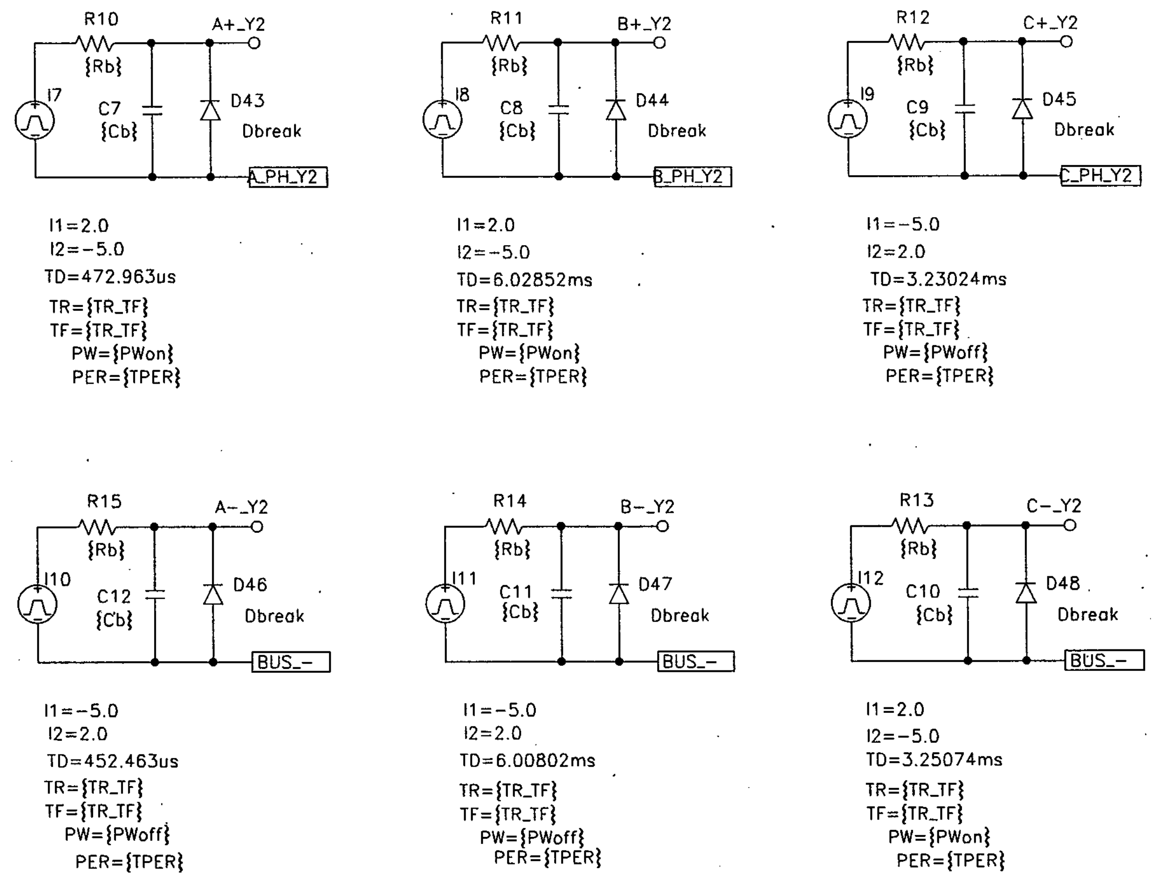

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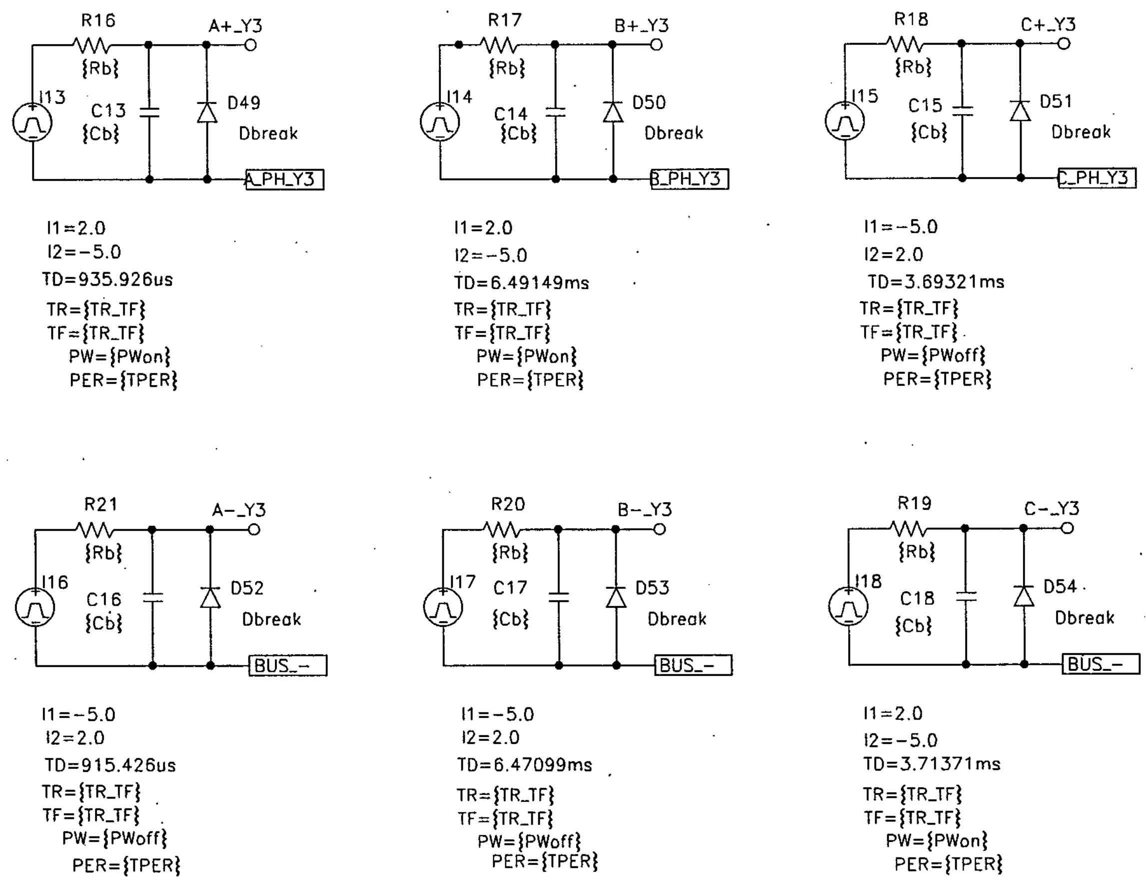

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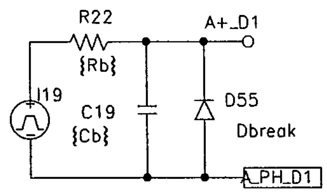

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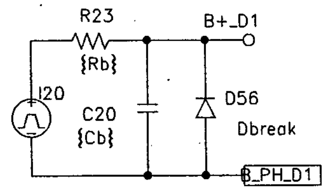

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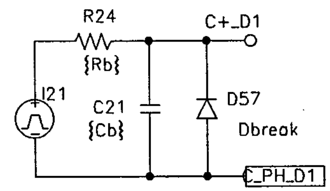

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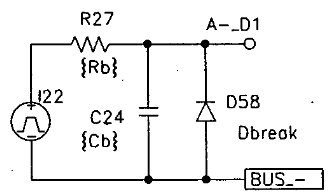

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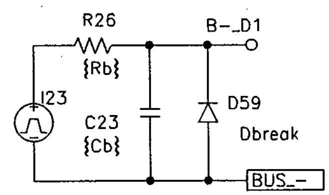

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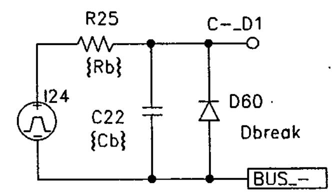

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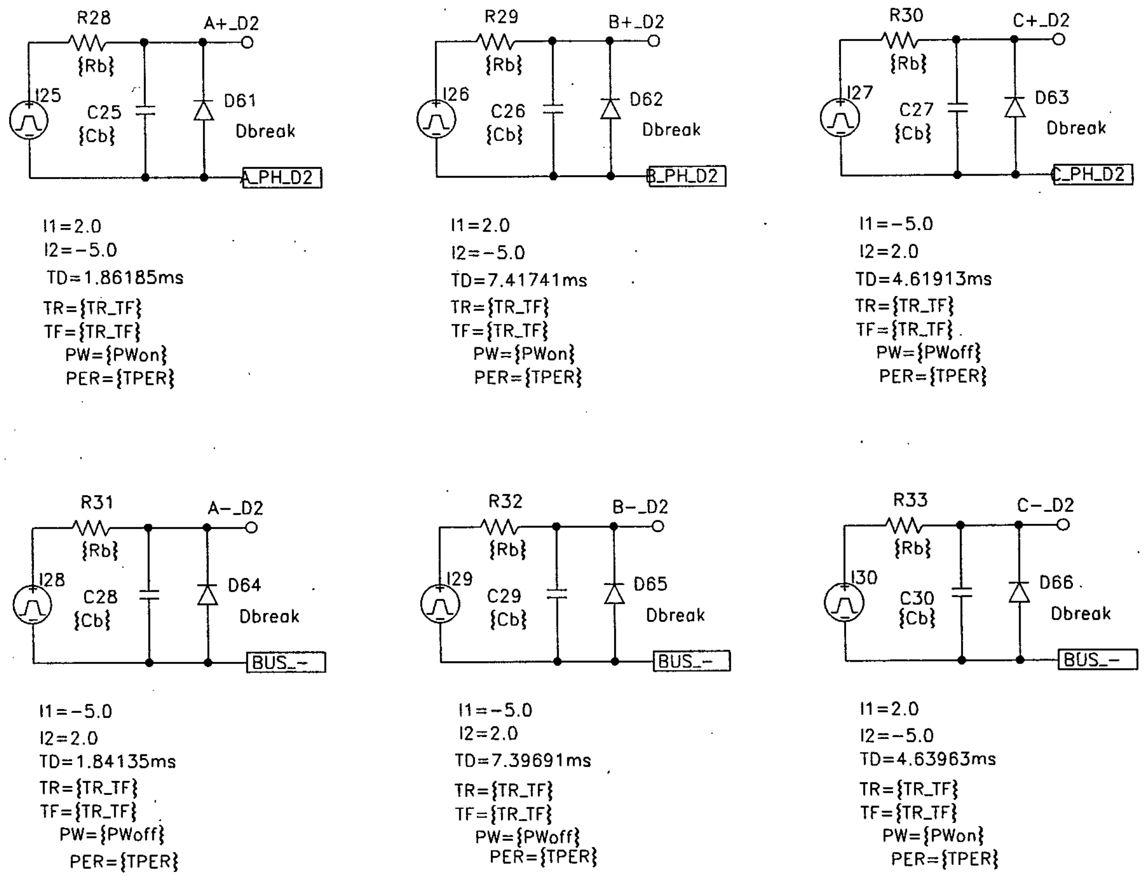

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BASE DRIVE SIGNALS DELTA 2

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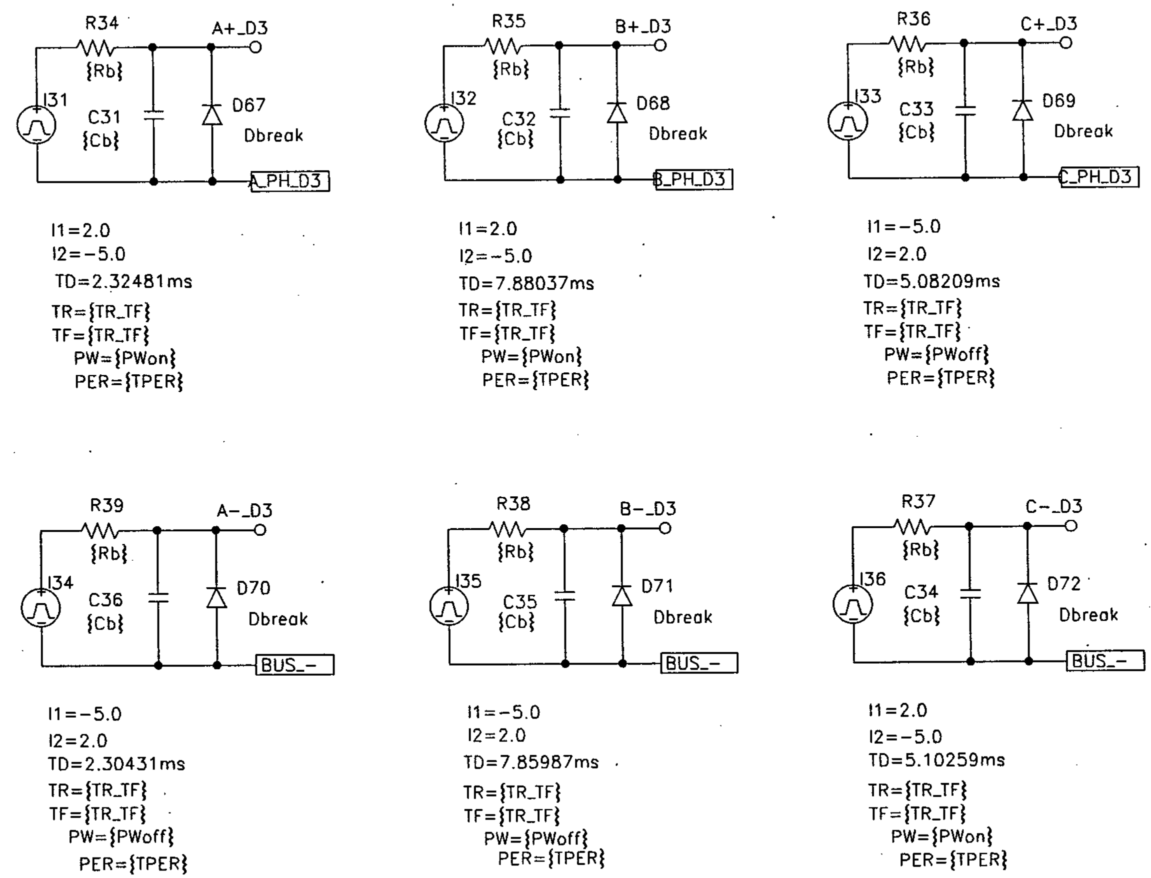

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BASE DRIVE SIGNALS DELTA 3

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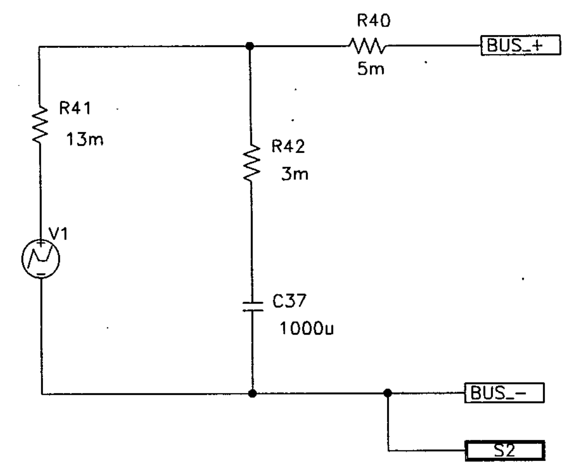

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LINK VOLTAGE SUPPLY

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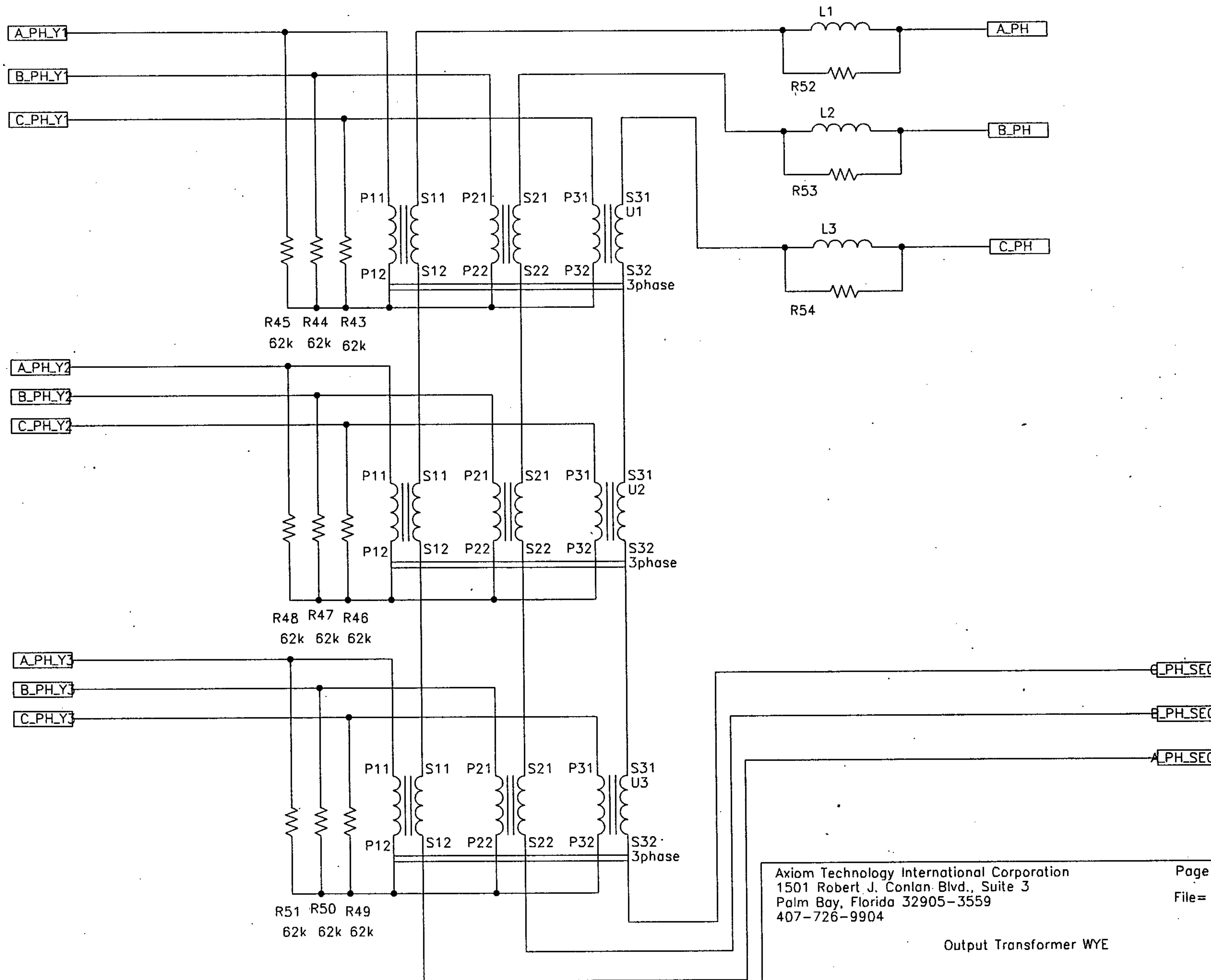

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Output Transformer WYE		
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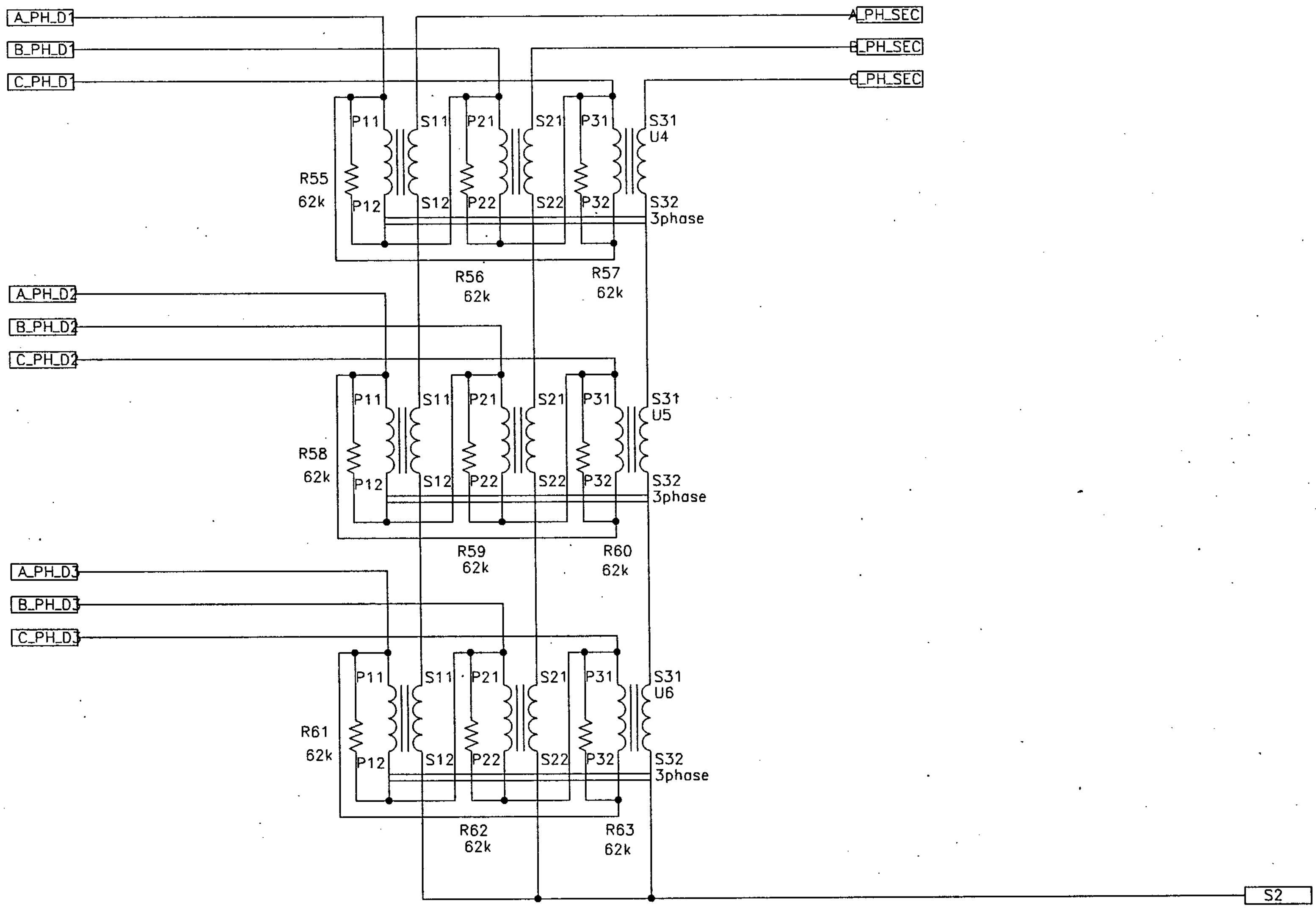

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OUTPUT TRANSFORMER DELTA

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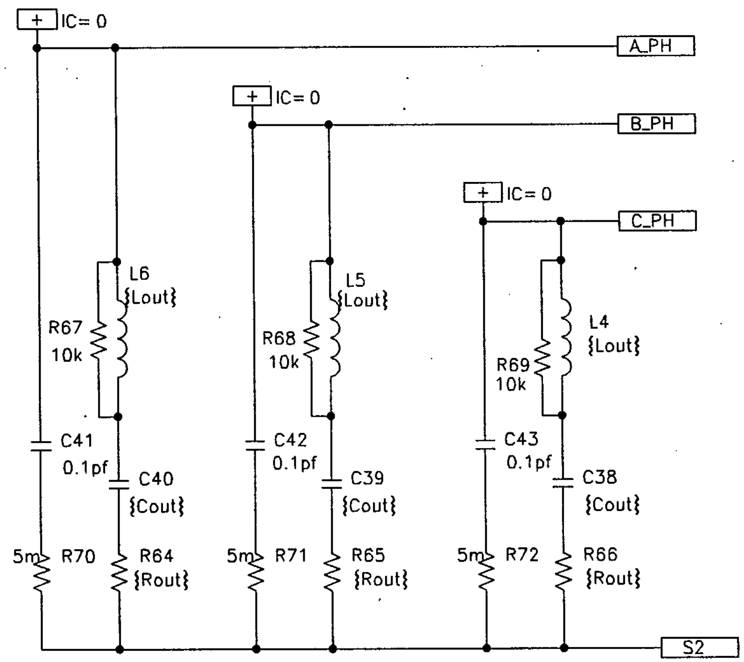

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Cout	20uf
Rout	0.05668

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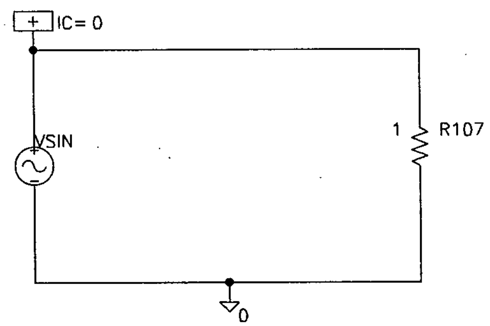
Output Filter

Revision: – 30 June 1995



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Sinewave reference

Revision: – January 1, 2000

Simulation Results

6 Bridge Configuration

Output Filtered

$R_L = 1.728\ \Omega$

$P_{OUT} = 100$ kW

**** 07/24/95 10:10:37 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(A_PH)

DC COMPONENT = -9.398568E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.383E+02	1.000E+00	-1.320E+02	0.000E+00
2	1.200E+02	8.413E-01	2.487E-03	-1.391E+02	-7.081E+00
3	1.800E+02	5.996E-02	1.773E-04	-3.222E+01	9.977E+01
4	2.400E+02	1.838E-02	5.434E-05	-9.162E+01	4.037E+01
5	3.000E+02	3.266E+00	9.655E-03	-1.164E+02	1.556E+01
6	3.600E+02	1.202E-01	3.554E-04	1.782E+02	3.102E+02
7	4.200E+02	1.521E+00	4.497E-03	-2.283E+01	1.092E+02
8	4.800E+02	5.969E-02	1.765E-04	-7.652E+01	5.546E+01
9	5.400E+02	8.226E-03	2.432E-05	1.268E+02	2.587E+02
10	6.000E+02	2.613E-02	7.724E-05	-1.157E+02	1.624E+01
11	6.600E+02	2.081E+00	6.152E-03	5.762E+00	1.378E+02
12	7.200E+02	1.912E-02	5.653E-05	4.486E+01	1.769E+02
13	7.800E+02	1.404E+00	4.151E-03	-7.148E+01	6.050E+01
14	8.400E+02	2.997E-02	8.860E-05	-1.612E+02	-2.925E+01
15	9.000E+02	4.441E-02	1.313E-04	3.994E+01	1.719E+02
16	9.600E+02	4.186E-02	1.238E-04	-9.502E+01	3.697E+01
17	1.020E+03	1.889E-01	5.585E-04	-4.447E+01	8.752E+01
18	1.080E+03	1.564E-02	4.623E-05	5.147E+01	1.835E+02
19	1.140E+03	2.035E-01	6.016E-04	4.995E+01	1.819E+02
20	1.200E+03	3.065E-02	9.061E-05	-1.231E+02	8.875E+00
21	1.260E+03	5.773E-02	1.707E-04	1.306E+02	2.626E+02
22	1.320E+03	4.217E-02	1.247E-04	-4.937E+01	8.262E+01
23	1.380E+03	4.992E-01	1.476E-03	8.384E+01	2.158E+02
24	1.440E+03	2.277E-02	6.731E-05	5.085E+01	1.828E+02
25	1.500E+03	4.478E-01	1.324E-03	6.951E+00	1.389E+02
26	1.560E+03	2.487E-02	7.353E-05	-1.022E+02	2.978E+01
27	1.620E+03	2.967E-02	8.773E-05	1.005E+02	2.324E+02
28	1.680E+03	5.671E-02	1.677E-04	-1.226E+02	9.360E+00
29	1.740E+03	1.730E-01	5.113E-04	6.612E+00	1.386E+02
30	1.800E+03	8.614E-02	2.547E-04	-2.574E+01	1.063E+02
31	1.860E+03	1.312E-01	3.879E-04	1.053E+02	2.373E+02
32	1.920E+03	5.464E-02	1.615E-04	7.169E+01	2.037E+02

33	1.980E+03	5.515E-02	1.630E-04	1.332E+02	2.652E+02
34	2.040E+03	4.046E-02	1.196E-04	9.218E+01	2.242E+02
35	2.100E+03	4.955E-01	1.465E-03	-9.429E+01	3.770E+01
36	2.160E+03	2.642E-02	7.811E-05	1.283E+02	2.602E+02
37	2.220E+03	8.253E-01	2.440E-03	2.375E+01	1.557E+02
38	2.280E+03	1.536E-02	4.541E-05	1.417E+02	2.737E+02
39	2.340E+03	4.463E-02	1.319E-04	1.402E+02	2.722E+02
40	2.400E+03	1.765E-02	5.218E-05	-1.665E+02	-3.448E+01
41	2.460E+03	5.413E-02	1.600E-04	8.646E+01	2.185E+02
42	2.520E+03	3.858E-02	1.140E-04	-5.368E+01	7.831E+01
43	2.580E+03	3.477E-02	1.028E-04	-1.353E+02	-3.352E+00
44	2.640E+03	2.925E-02	8.647E-05	2.117E+01	1.532E+02
45	2.700E+03	7.831E-03	2.315E-05	-1.362E+02	-4.219E+00
46	2.760E+03	3.646E-02	1.078E-04	5.452E+01	1.865E+02
47	2.820E+03	1.051E-01	3.107E-04	-1.628E+02	-3.079E+01
48	2.880E+03	5.961E-03	1.762E-05	1.795E+02	3.115E+02
49	2.940E+03	9.079E-02	2.684E-04	1.286E+02	2.606E+02
50	3.000E+03	2.835E-02	8.381E-05	3.874E+01	1.707E+02
51	3.060E+03	1.834E-02	5.422E-05	-1.382E+02	-6.247E+00
52	3.120E+03	2.248E-02	6.646E-05	1.307E+02	2.627E+02
53	3.180E+03	9.293E-03	2.747E-05	1.608E+02	2.928E+02
54	3.240E+03	1.253E-02	3.706E-05	-5.582E+01	7.617E+01
55	3.300E+03	2.700E-02	7.982E-05	-1.536E+02	-2.159E+01
56	3.360E+03	2.586E-02	7.645E-05	9.180E+01	2.238E+02
57	3.420E+03	2.535E-02	7.496E-05	-6.142E+01	7.057E+01
58	3.480E+03	1.784E-02	5.273E-05	1.691E+02	3.011E+02
59	3.540E+03	5.115E-02	1.512E-04	-5.538E+01	7.661E+01
60	3.600E+03	1.140E-02	3.370E-05	-1.538E+02	-2.184E+01
61	3.660E+03	7.601E-02	2.247E-04	-1.364E+02	-4.423E+00
62	3.720E+03	6.408E-03	1.894E-05	-1.338E+02	-1.850E+00
63	3.780E+03	5.791E-03	1.712E-05	1.643E+01	1.484E+02
64	3.840E+03	9.535E-03	2.819E-05	2.405E+00	1.344E+02
65	3.900E+03	3.108E-02	9.187E-05	-1.167E+02	1.526E+01
66	3.960E+03	9.427E-03	2.787E-05	1.232E+02	2.552E+02
67	4.020E+03	3.166E-02	9.358E-05	-1.890E+00	1.301E+02
68	4.080E+03	4.649E-03	1.374E-05	-8.357E+01	4.842E+01
69	4.140E+03	8.154E-03	2.411E-05	-1.486E+01	1.171E+02
70	4.200E+03	1.120E-02	3.312E-05	-1.970E+00	1.300E+02
71	4.260E+03	4.727E-01	1.397E-03	6.080E+01	1.928E+02
72	4.320E+03	5.589E-03	1.652E-05	-6.461E-01	1.313E+02
73	4.380E+03	4.556E-01	1.347E-03	1.694E+02	3.014E+02
74	4.440E+03	3.184E-03	9.414E-06	5.755E+01	1.895E+02
75	4.500E+03	7.132E-03	2.108E-05	-4.991E+00	1.270E+02
76	4.560E+03	3.995E-03	1.181E-05	-5.087E+01	8.112E+01
77	4.620E+03	2.286E-02	6.758E-05	-1.726E+02	-4.064E+01
78	4.680E+03	3.829E-03	1.132E-05	1.455E+02	2.774E+02
79	4.740E+03	2.028E-02	5.996E-05	-7.024E+01	6.175E+01
80	4.800E+03	6.309E-03	1.865E-05	-1.039E+02	2.813E+01

TOTAL HARMONIC DISTORTION = 1.387315E+00 PERCENT

**** 07/24/95 10:10:37 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

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FOURIER COMPONENTS OF TRANSIENT RESPONSE V(B_PH)

DC COMPONENT = 8.677982E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.382E+02	1.000E+00	1.080E+02	0.000E+00
2	1.200E+02	8.176E-01	2.417E-03	9.819E+01	-9.813E+00
3	1.800E+02	4.217E-02	1.247E-04	1.498E+02	4.178E+01
4	2.400E+02	9.536E-03	2.819E-05	-1.292E+02	-2.372E+02
5	3.000E+02	3.301E+00	9.760E-03	2.775E+00	-1.052E+02
6	3.600E+02	1.183E-01	3.497E-04	2.406E+01	-8.395E+01
7	4.200E+02	1.574E+00	4.653E-03	-1.411E+02	-2.491E+02
8	4.800E+02	7.733E-02	2.286E-04	-1.618E+02	-2.698E+02
9	5.400E+02	4.972E-02	1.470E-04	1.724E+02	6.443E+01
10	6.000E+02	2.424E-02	7.166E-05	6.201E+01	-4.599E+01
11	6.600E+02	2.106E+00	6.226E-03	1.242E+02	1.623E+01
12	7.200E+02	2.623E-02	7.754E-05	-1.311E+02	-2.391E+02
13	7.800E+02	1.408E+00	4.162E-03	1.677E+02	5.967E+01
14	8.400E+02	1.549E-02	4.578E-05	-1.162E+02	-2.242E+02
15	9.000E+02	2.552E-02	7.546E-05	-1.735E+02	-2.815E+02
16	9.600E+02	3.199E-02	9.459E-05	9.658E+01	-1.142E+01
17	1.020E+03	2.405E-01	7.111E-04	6.806E+01	-3.995E+01
18	1.080E+03	2.225E-02	6.577E-05	-1.528E+02	-2.608E+02
19	1.140E+03	1.596E-01	4.718E-04	-7.301E+01	-1.810E+02
20	1.200E+03	2.728E-02	8.065E-05	2.116E+01	-8.685E+01
21	1.260E+03	3.522E-02	1.041E-04	-6.092E+01	-1.689E+02
22	1.320E+03	1.328E-02	3.926E-05	-1.053E+02	-2.133E+02
23	1.380E+03	4.980E-01	1.472E-03	-1.634E+02	-2.714E+02
24	1.440E+03	4.220E-02	1.248E-04	-1.214E+02	-2.294E+02
25	1.500E+03	3.687E-01	1.090E-03	-1.219E+02	-2.299E+02
26	1.560E+03	2.872E-02	8.490E-05	5.544E+01	-5.257E+01
27	1.620E+03	1.106E-01	3.269E-04	-1.948E+01	-1.275E+02
28	1.680E+03	6.572E-02	1.943E-04	-3.739E+01	-1.454E+02
29	1.740E+03	1.470E-01	4.346E-04	1.510E+02	4.302E+01
30	1.800E+03	1.030E-01	3.046E-04	1.656E+02	5.764E+01
31	1.860E+03	1.102E-01	3.259E-04	-2.610E+01	-1.341E+02
32	1.920E+03	4.184E-03	1.237E-05	1.582E+02	5.015E+01

33	1.980E+03	3.678E-02	1.087E-04	-1.315E+02	-2.395E+02
34	2.040E+03	1.203E-02	3.557E-05	-1.261E+02	-2.342E+02
35	2.100E+03	5.335E-01	1.577E-03	3.565E+01	-7.236E+01
36	2.160E+03	2.796E-03	8.266E-06	5.590E+01	-5.211E+01
37	2.220E+03	8.108E-01	2.397E-03	-1.034E+02	-2.115E+02
38	2.280E+03	3.486E-03	1.031E-05	-1.623E+02	-2.703E+02
39	2.340E+03	4.696E-02	1.388E-04	3.675E+01	-7.126E+01
40	2.400E+03	5.579E-03	1.649E-05	-1.443E+02	-2.523E+02
41	2.460E+03	4.420E-02	1.307E-04	-1.488E+02	-2.568E+02
42	2.520E+03	3.371E-02	9.967E-05	9.356E+01	-1.445E+01
43	2.580E+03	6.837E-02	2.021E-04	5.746E+01	-5.055E+01
44	2.640E+03	1.148E-02	3.395E-05	-3.494E+01	-1.429E+02
45	2.700E+03	5.334E-02	1.577E-04	-4.565E+01	-1.537E+02
46	2.760E+03	2.209E-02	6.532E-05	-1.307E+02	-2.387E+02
47	2.820E+03	9.847E-02	2.911E-04	-6.968E+01	-1.777E+02
48	2.880E+03	2.663E-02	7.874E-05	5.052E+01	-5.749E+01
49	2.940E+03	8.709E-02	2.575E-04	-1.066E+01	-1.187E+02
50	3.000E+03	7.836E-03	2.317E-05	1.632E+02	5.520E+01
51	3.060E+03	3.779E-03	1.117E-05	9.609E+01	-1.192E+01
52	3.120E+03	1.998E-02	5.906E-05	-3.091E+01	-1.389E+02
53	3.180E+03	1.929E-02	5.703E-05	-1.121E+02	-2.201E+02
54	3.240E+03	1.173E-02	3.469E-05	1.310E+02	2.297E+01
55	3.300E+03	6.024E-03	1.781E-05	-8.946E+01	-1.975E+02
56	3.360E+03	1.802E-02	5.329E-05	-1.189E+02	-2.269E+02
57	3.420E+03	2.362E-02	6.982E-05	1.136E+02	5.600E+00
58	3.480E+03	1.079E-02	3.190E-05	6.807E+01	-3.994E+01
59	3.540E+03	4.660E-02	1.378E-04	3.929E+01	-6.872E+01
60	3.600E+03	4.527E-03	1.339E-05	-2.284E+01	-1.308E+02
61	3.660E+03	5.905E-02	1.746E-04	1.015E+02	-6.497E+00
62	3.720E+03	3.957E-03	1.170E-05	-1.559E+02	-2.639E+02
63	3.780E+03	2.025E-02	5.988E-05	-1.772E+02	-2.852E+02
64	3.840E+03	1.368E-02	4.045E-05	1.413E+02	3.325E+01
65	3.900E+03	3.811E-02	1.127E-04	2.261E+01	-8.540E+01
66	3.960E+03	1.055E-02	3.118E-05	-2.911E+01	-1.371E+02
67	4.020E+03	3.484E-02	1.030E-04	-1.038E+02	-2.118E+02
68	4.080E+03	4.432E-03	1.310E-05	5.826E+01	-4.975E+01
69	4.140E+03	9.590E-03	2.835E-05	-1.784E+02	-2.864E+02
70	4.200E+03	6.320E-03	1.869E-05	1.237E+02	1.567E+01
71	4.260E+03	4.661E-01	1.378E-03	-1.792E+02	-2.872E+02
72	4.320E+03	6.792E-03	2.008E-05	-4.064E+01	-1.486E+02
73	4.380E+03	4.622E-01	1.367E-03	4.866E+01	-5.935E+01
74	4.440E+03	4.974E-03	1.471E-05	-1.201E+02	-2.281E+02
75	4.500E+03	4.232E-03	1.251E-05	-9.466E+01	-2.027E+02
76	4.560E+03	3.836E-03	1.134E-05	1.098E+02	1.823E+00
77	4.620E+03	2.751E-02	8.134E-05	-5.530E+01	-1.633E+02
78	4.680E+03	9.091E-03	2.688E-05	-4.058E+01	-1.486E+02
79	4.740E+03	1.484E-02	4.387E-05	1.660E+02	5.802E+01
80	4.800E+03	2.992E-03	8.845E-06	-1.592E+02	-2.672E+02

TOTAL HARMONIC DISTORTION = 1.400465E+00 PERCENT

**** 07/24/95 10:10:37 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

****   FOURIER ANALYSIS   TEMPERATURE = 27.000 DEG C

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FOURIER COMPONENTS OF TRANSIENT RESPONSE V(C_PH)

DC COMPONENT = 7.205782E-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.382E+02	1.000E+00	-1.199E+01	0.000E+00
2	1.200E+02	7.952E-01	2.351E-03	-1.894E+01	-6.955E+00
3	1.800E+02	1.787E-02	5.284E-05	1.430E+02	1.550E+02
4	2.400E+02	2.659E-02	7.860E-05	7.575E+01	8.774E+01
5	3.000E+02	3.323E+00	9.826E-03	1.237E+02	1.357E+02
6	3.600E+02	5.333E-02	1.577E-04	-7.685E+01	-6.486E+01
7	4.200E+02	1.588E+00	4.694E-03	9.638E+01	1.084E+02
8	4.800E+02	1.015E-01	3.002E-04	5.410E+01	6.609E+01
9	5.400E+02	5.578E-02	1.649E-04	-1.362E+01	-1.638E+00
10	6.000E+02	2.131E-03	6.301E-06	9.065E+01	1.026E+02
11	6.600E+02	2.142E+00	6.332E-03	-1.144E+02	-1.024E+02
12	7.200E+02	7.279E-03	2.152E-05	5.966E+01	7.165E+01
13	7.800E+02	1.388E+00	4.104E-03	4.796E+01	5.995E+01
14	8.400E+02	4.236E-02	1.252E-04	3.375E+01	4.573E+01
15	9.000E+02	2.705E-02	7.996E-05	-1.087E+02	-9.676E+01
16	9.600E+02	1.234E-02	3.648E-05	5.353E+01	6.551E+01
17	1.020E+03	2.423E-01	7.165E-04	-1.580E+02	-1.460E+02
18	1.080E+03	1.025E-02	3.032E-05	-1.162E+01	3.646E-01
19	1.140E+03	1.776E-01	5.251E-04	-1.790E+02	-1.670E+02
20	1.200E+03	1.806E-02	5.340E-05	1.188E+02	1.308E+02
21	1.260E+03	2.428E-02	7.177E-05	-3.244E+01	-2.045E+01
22	1.320E+03	5.080E-02	1.502E-04	1.181E+02	1.301E+02
23	1.380E+03	5.519E-01	1.632E-03	-3.987E+01	-2.788E+01
24	1.440E+03	1.988E-02	5.878E-05	6.752E+01	7.951E+01
25	1.500E+03	3.594E-01	1.062E-03	1.340E+02	1.460E+02
26	1.560E+03	1.105E-02	3.267E-05	1.766E+02	1.886E+02
27	1.620E+03	9.916E-02	2.932E-04	1.756E+02	1.875E+02
28	1.680E+03	9.030E-02	2.670E-04	1.039E+02	1.159E+02
29	1.740E+03	1.008E-01	2.981E-04	-1.154E+02	-1.034E+02
30	1.800E+03	2.518E-02	7.444E-05	2.811E+01	4.010E+01
31	1.860E+03	1.012E-01	2.993E-04	-1.295E+02	-1.175E+02
32	1.920E+03	5.505E-02	1.628E-04	-1.040E+02	-9.197E+01

33	1.980E+03	6.344E-02	1.876E-04	-1.149E+01	4.915E-01
34	2.040E+03	3.191E-02	9.434E-05	-7.430E+01	-6.232E+01
35	2.100E+03	4.367E-01	1.291E-03	1.552E+02	1.672E+02
36	2.160E+03	2.740E-02	8.100E-05	-5.733E+01	-4.534E+01
37	2.220E+03	7.277E-01	2.151E-03	1.412E+02	1.532E+02
38	2.280E+03	1.755E-02	5.188E-05	-2.884E+01	-1.686E+01
39	2.340E+03	5.676E-02	1.678E-04	-9.337E+01	-8.139E+01
40	2.400E+03	2.291E-02	6.775E-05	1.880E+01	3.078E+01
41	2.460E+03	4.647E-02	1.374E-04	-4.209E+01	-3.010E+01
42	2.520E+03	2.092E-02	6.184E-05	-1.730E+02	-1.610E+02
43	2.580E+03	3.531E-02	1.044E-04	-1.099E+02	-9.796E+01
44	2.640E+03	3.690E-02	1.091E-04	-1.738E+02	-1.618E+02
45	2.700E+03	5.384E-02	1.592E-04	1.260E+02	1.380E+02
46	2.760E+03	1.460E-02	4.316E-05	-1.176E+02	-1.056E+02
47	2.820E+03	1.401E-01	4.142E-04	6.181E+01	7.379E+01
48	2.880E+03	2.335E-02	6.903E-05	-1.180E+02	-1.061E+02
49	2.940E+03	6.197E-02	1.832E-04	-1.178E+02	-1.058E+02
50	3.000E+03	2.477E-02	7.324E-05	-1.261E+02	-1.142E+02
51	3.060E+03	1.643E-02	4.856E-05	3.099E+01	4.298E+01
52	3.120E+03	7.224E-03	2.136E-05	-1.101E+02	-9.810E+01
53	3.180E+03	2.183E-02	6.455E-05	4.274E+01	5.472E+01
54	3.240E+03	1.647E-03	4.869E-06	6.666E+01	7.865E+01
55	3.300E+03	3.012E-02	8.906E-05	3.679E+01	4.878E+01
56	3.360E+03	1.385E-02	4.095E-05	-4.660E+01	-3.461E+01
57	3.420E+03	2.746E-03	8.120E-06	1.669E+02	1.789E+02
58	3.480E+03	1.900E-02	5.618E-05	-4.480E+01	-3.281E+01
59	3.540E+03	6.633E-02	1.961E-04	1.691E+02	1.810E+02
60	3.600E+03	9.096E-03	2.689E-05	4.824E+01	6.023E+01
61	3.660E+03	6.706E-02	1.983E-04	-4.663E+00	7.323E+00
62	3.720E+03	1.018E-02	3.011E-05	3.776E+01	4.975E+01
63	3.780E+03	1.469E-02	4.343E-05	-2.531E+00	9.455E+00
64	3.840E+03	9.036E-03	2.671E-05	-8.273E+01	-7.074E+01
65	3.900E+03	2.493E-02	7.370E-05	1.483E+02	1.603E+02
66	3.960E+03	4.904E-03	1.450E-05	-1.458E+02	-1.338E+02
67	4.020E+03	4.195E-02	1.240E-04	1.238E+02	1.357E+02
68	4.080E+03	2.977E-03	8.801E-06	1.634E+02	1.754E+02
69	4.140E+03	2.906E-03	8.591E-06	5.407E+01	6.605E+01
70	4.200E+03	9.105E-03	2.692E-05	-1.476E+02	-1.356E+02
71	4.260E+03	4.695E-01	1.388E-03	-5.991E+01	-4.792E+01
72	4.320E+03	1.164E-02	3.442E-05	1.573E+02	1.693E+02
73	4.380E+03	4.537E-01	1.341E-03	-7.169E+01	-5.971E+01
74	4.440E+03	1.798E-03	5.315E-06	6.408E+01	7.607E+01
75	4.500E+03	8.313E-03	2.458E-05	1.444E+02	1.564E+02
76	4.560E+03	1.322E-03	3.909E-06	-1.574E+02	-1.454E+02
77	4.620E+03	2.650E-02	7.835E-05	7.466E+01	8.664E+01
78	4.680E+03	5.299E-03	1.567E-05	1.351E+02	1.471E+02
79	4.740E+03	1.724E-02	5.097E-05	6.407E+01	7.605E+01
80	4.800E+03	8.380E-03	2.478E-05	5.906E+01	7.104E+01

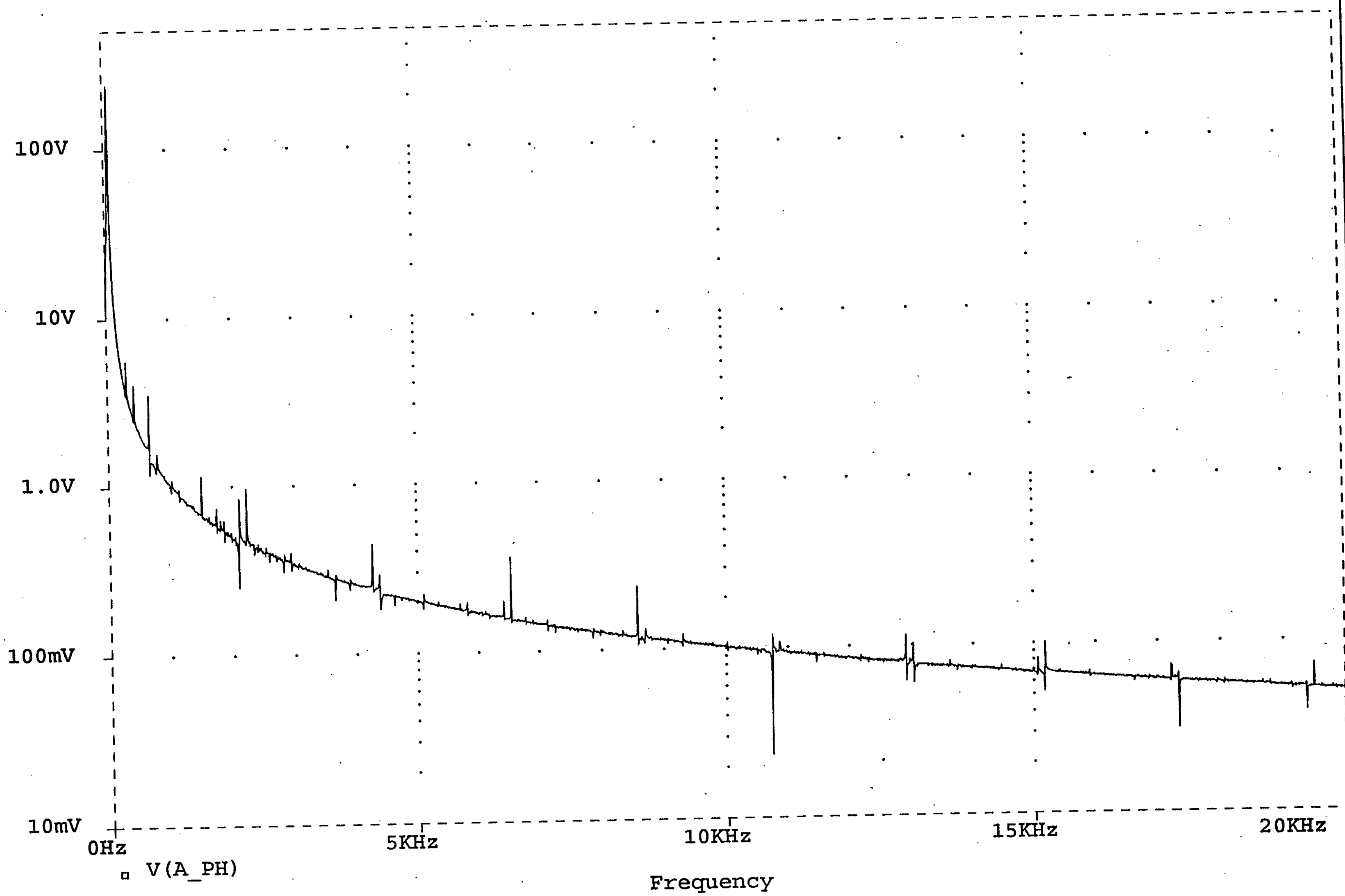
TOTAL HARMONIC DISTORTION = 1.402614E+00 PERCENT

JOB CONCLUDED

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

(N) A Phase Output Voltage FFT - expanded

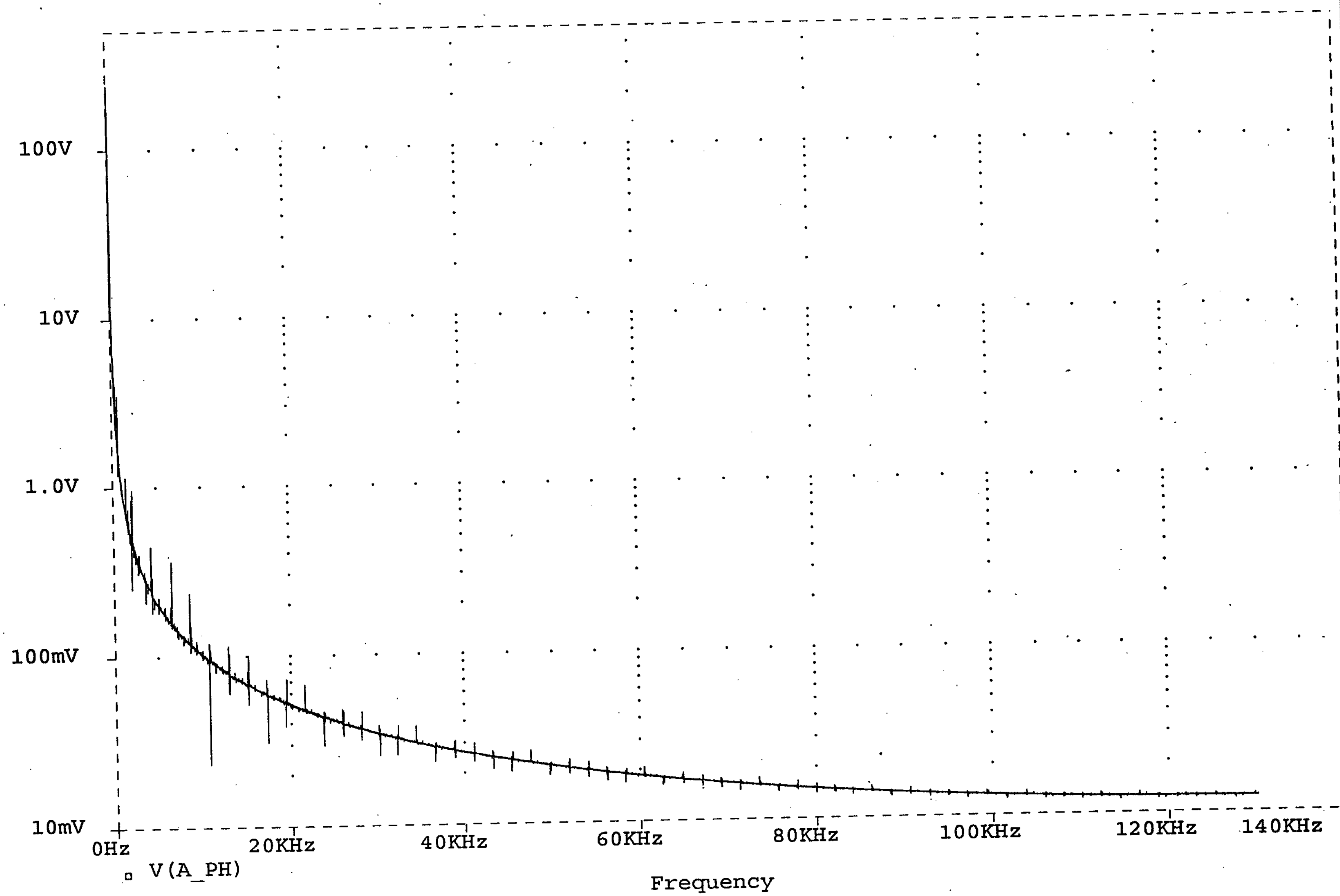


Date: July 24, 1995 Page 1 Time: 11:25:13

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

(M) A Phase Output Voltage FFT

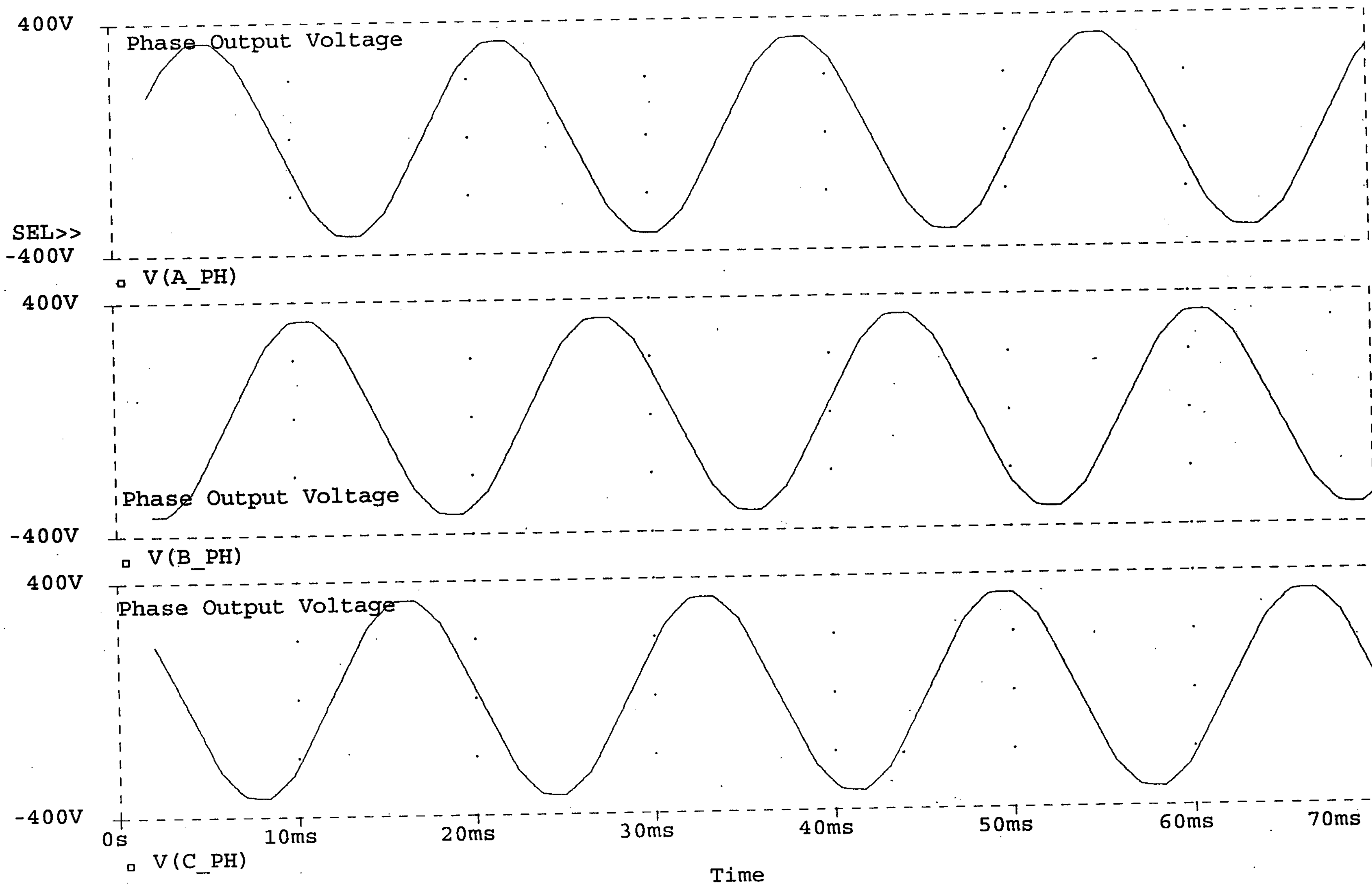


Date: July 24, 1995 Page 2 Time: 11:25:47

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

(G) 3 Phase Output Voltages (l-n)

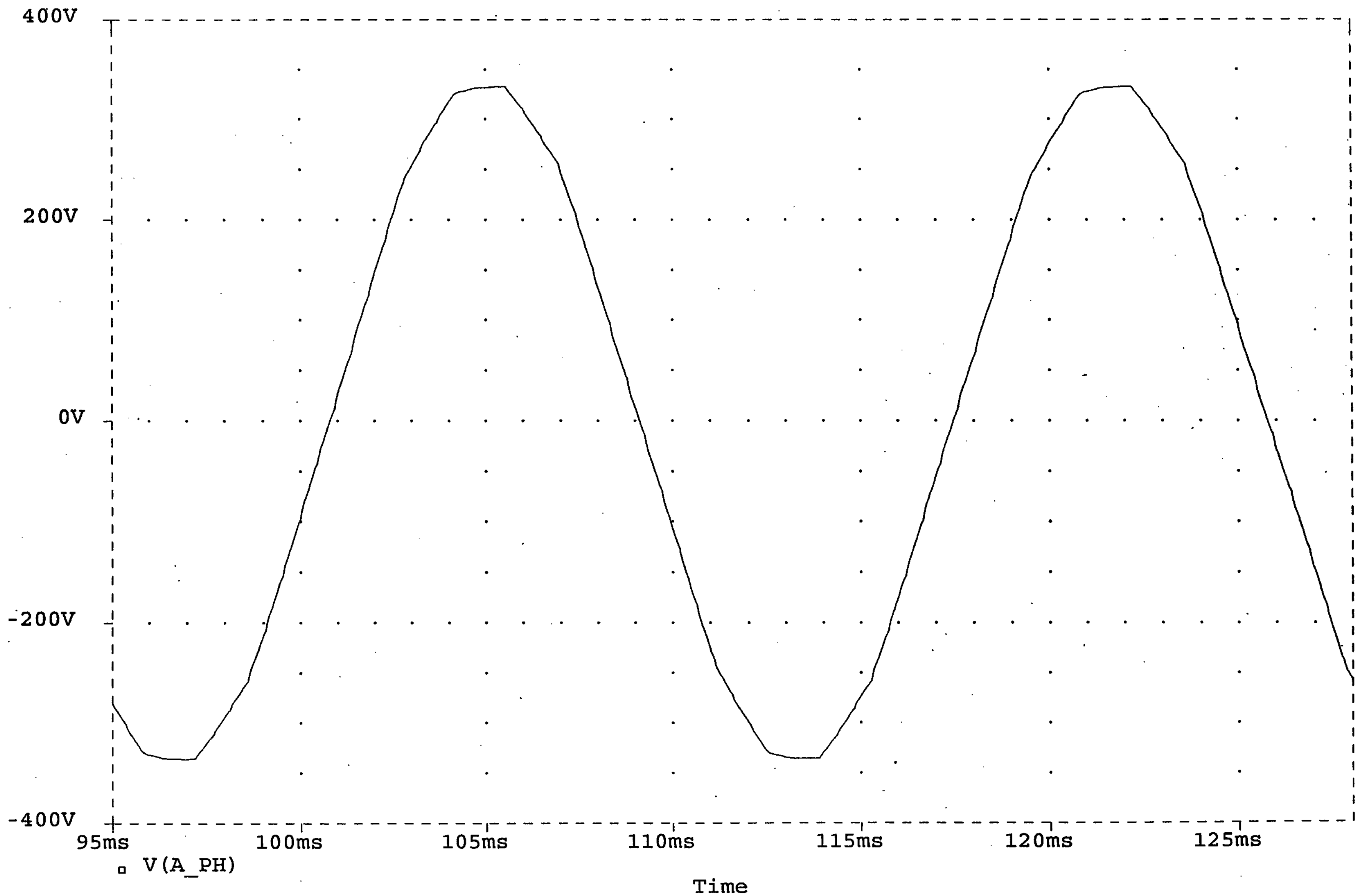


Date: July 24, 1995 Page 3 Time: 11:27:46

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

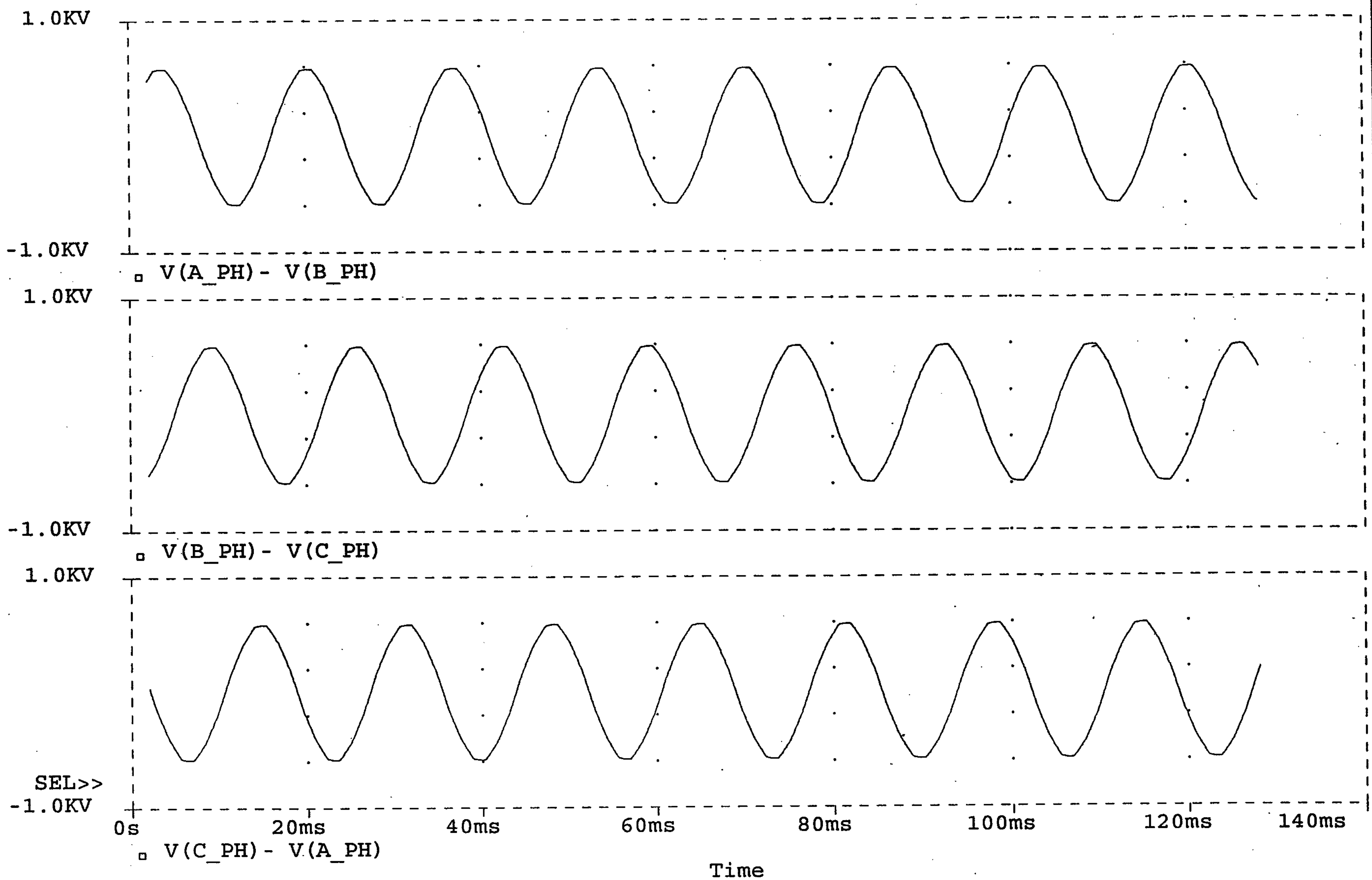
(J) A Phase Output Voltage - expanded



* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

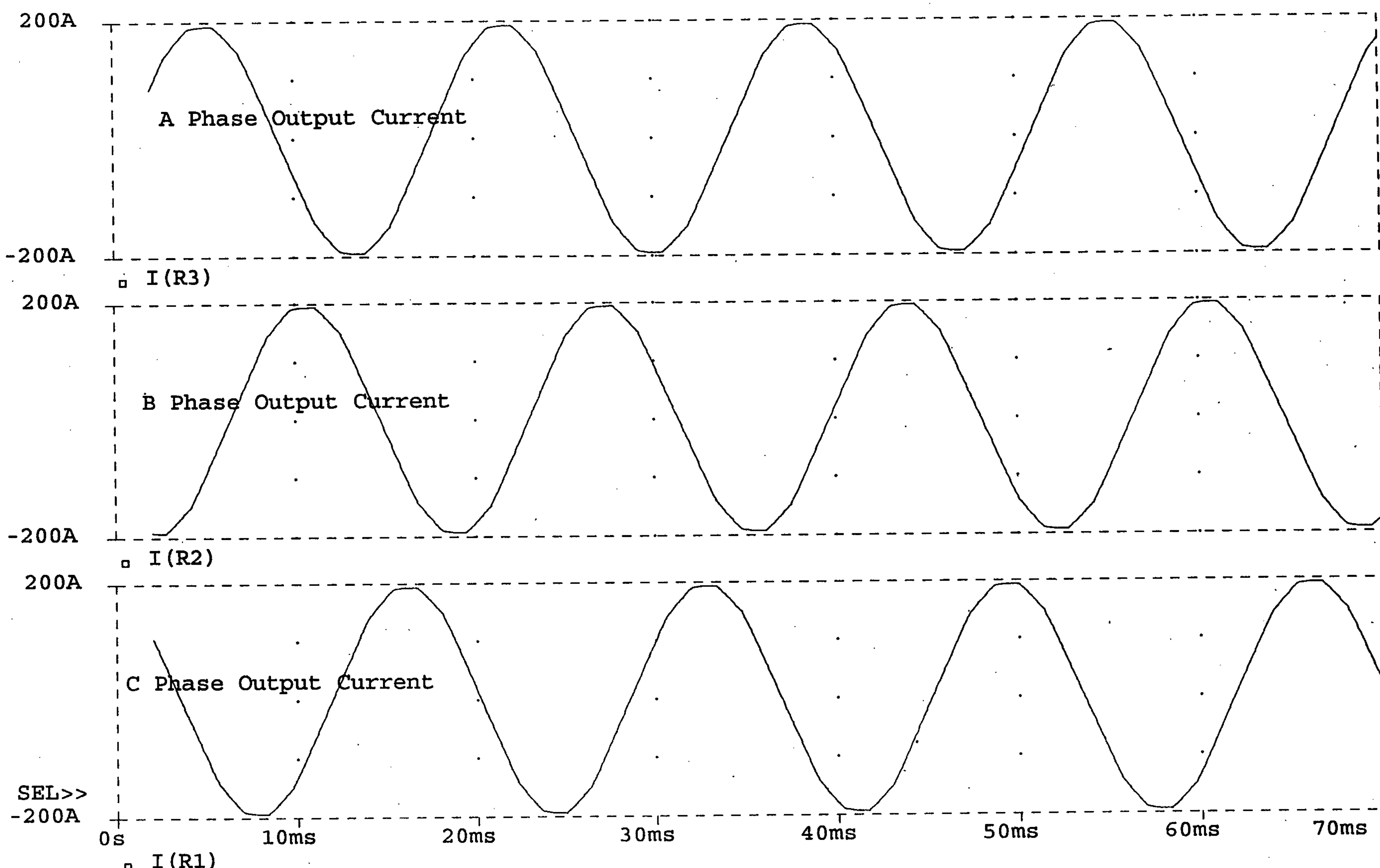
(K) 3 Phase Output Voltages (1-1)



* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/24/95 10:10:37 Temperature: 27.0

(L) 3 Phase Output Currents



Simulation Results

6 Bridge Configuration

Output Filtered

R_L= 1000 Ω

P_{OUT} = Approximately No Load

**** 07/26/95 10:28:56 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(A_PH)

DC COMPONENT = -6.407457E-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.466E+02	1.000E+00	-1.249E+02	0.000E+00
2	1.200E+02	3.021E-01	8.716E-04	-8.709E+01	3.781E+01
3	1.800E+02	2.749E-02	7.933E-05	2.933E+01	1.542E+02
4	2.400E+02	8.840E-02	2.551E-04	-1.092E+02	1.568E+01

5	3.000E+02	3.946E+00	1.139E-02	-8.347E+01	4.143E+01
6	3.600E+02	1.667E-01	4.810E-04	-7.595E+01	4.895E+01
7	4.200E+02	2.227E+00	6.426E-03	2.274E+01	1.476E+02
8	4.800E+02	1.024E-01	2.955E-04	3.250E+01	1.574E+02
9	5.400E+02	7.390E-03	2.132E-05	4.671E+01	1.716E+02
10	6.000E+02	9.117E-02	2.631E-04	-1.031E+02	2.177E+01
11	6.600E+02	4.366E+00	1.260E-02	6.479E+01	1.897E+02
12	7.200E+02	1.323E-01	3.818E-04	-4.662E+00	1.202E+02
13	7.800E+02	3.839E+00	1.108E-02	-6.539E+00	1.184E+02
14	8.400E+02	2.048E-01	5.910E-04	-6.496E+01	5.995E+01
15	9.000E+02	1.944E-01	5.611E-04	-9.849E+01	2.641E+01
16	9.600E+02	2.757E-01	7.955E-04	-2.893E+01	9.597E+01
17	1.020E+03	1.781E+00	5.140E-03	2.679E+01	1.517E+02
18	1.080E+03	3.097E-01	8.937E-04	-1.243E+02	6.218E-01
19	1.140E+03	3.606E+00	1.040E-02	1.178E+02	2.427E+02
20	1.200E+03	2.111E+00	6.090E-03	1.710E+02	2.959E+02
21	1.260E+03	9.687E-01	2.795E-03	-1.287E+02	-3.778E+00
22	1.320E+03	5.112E-01	1.475E-03	-1.303E+02	-5.358E+00
23	1.380E+03	2.112E+00	6.093E-03	1.192E+01	1.368E+02
24	1.440E+03	2.336E-01	6.741E-04	8.200E+01	2.069E+02
25	1.500E+03	7.664E-01	2.211E-03	-5.453E+01	7.037E+01
26	1.560E+03	1.079E-01	3.114E-04	-1.765E+02	-5.160E+01
27	1.620E+03	2.051E-01	5.917E-04	1.256E+02	2.505E+02
28	1.680E+03	1.604E-01	4.629E-04	1.244E+02	2.493E+02
29	1.740E+03	2.235E-01	6.449E-04	6.450E+01	1.894E+02
30	1.800E+03	2.315E-01	6.678E-04	-1.377E+02	-1.283E+01
31	1.860E+03	7.790E-02	2.248E-04	1.366E+02	2.616E+02
32	1.920E+03	1.360E-01	3.925E-04	-1.129E+01	1.136E+02
33	1.980E+03	1.029E-01	2.970E-04	5.964E+01	1.845E+02
34	2.040E+03	9.847E-02	2.841E-04	2.033E+01	1.452E+02
35	2.100E+03	6.336E-01	1.828E-03	-1.033E+02	2.161E+01
36	2.160E+03	9.198E-02	2.654E-04	1.205E+02	2.454E+02
37	2.220E+03	8.647E-01	2.495E-03	3.002E+01	1.549E+02
38	2.280E+03	4.828E-02	1.393E-04	1.768E+02	3.017E+02
39	2.340E+03	3.415E-02	9.855E-05	-1.508E+02	-2.588E+01
40	2.400E+03	3.473E-03	1.002E-05	-8.729E+01	3.761E+01
41	2.460E+03	8.795E-02	2.538E-04	1.099E+02	2.348E+02
42	2.520E+03	6.631E-02	1.913E-04	1.113E+02	2.362E+02
43	2.580E+03	1.177E-01	3.396E-04	-1.624E+02	-3.754E+01
44	2.640E+03	7.159E-02	2.066E-04	-1.792E+02	-5.427E+01
45	2.700E+03	6.390E-02	1.844E-04	-1.676E+02	-4.270E+01
46	2.760E+03	4.031E-02	1.163E-04	1.625E+02	2.874E+02

47	2.820E+03	1.882E-01	5.431E-04	-1.329E+02	-7.978E+00
48	2.880E+03	1.883E-02	5.433E-05	-1.370E+02	-1.207E+01
49	2.940E+03	1.581E-01	4.562E-04	1.652E+02	2.901E+02
50	3.000E+03	1.921E-02	5.542E-05	7.232E+01	1.972E+02
51	3.060E+03	1.872E-02	5.402E-05	1.701E+02	2.950E+02
52	3.120E+03	1.178E-02	3.400E-05	-2.137E+01	1.035E+02
53	3.180E+03	6.731E-02	1.942E-04	1.662E+02	2.911E+02
54	3.240E+03	4.040E-02	1.166E-04	6.496E+01	1.899E+02
55	3.300E+03	8.580E-02	2.476E-04	-1.047E+02	2.022E+01
56	3.360E+03	3.048E-02	8.794E-05	-7.031E+01	5.460E+01
57	3.420E+03	3.005E-02	8.671E-05	-1.031E+02	2.180E+01
58	3.480E+03	1.951E-02	5.630E-05	1.232E+02	2.481E+02
59	3.540E+03	1.203E-01	3.470E-04	3.254E+01	1.574E+02
60	3.600E+03	6.679E-03	1.927E-05	1.167E+02	2.416E+02
61	3.660E+03	1.089E-01	3.141E-04	-6.177E+01	6.313E+01
62	3.720E+03	3.802E-02	1.097E-04	1.403E+02	2.652E+02
63	3.780E+03	4.096E-02	1.182E-04	1.126E+02	2.375E+02
64	3.840E+03	1.044E-02	3.012E-05	1.762E+02	3.011E+02
65	3.900E+03	4.200E-02	1.212E-04	3.192E+00	1.281E+02
66	3.960E+03	4.976E-02	1.436E-04	-1.451E+02	-2.024E+01
67	4.020E+03	6.958E-02	2.008E-04	9.892E+01	2.238E+02
68	4.080E+03	1.032E-02	2.978E-05	-1.276E+02	-2.687E+00
69	4.140E+03	1.628E-02	4.696E-05	-1.214E+02	3.503E+00
70	4.200E+03	4.381E-02	1.264E-04	-1.008E+02	2.408E+01
71	4.260E+03	1.328E+00	3.832E-03	1.237E+02	2.486E+02
72	4.320E+03	3.188E-02	9.199E-05	2.790E+01	1.528E+02
73	4.380E+03	1.320E+00	3.809E-03	-1.284E+02	-3.471E+00
74	4.440E+03	2.530E-02	7.299E-05	1.666E+02	2.915E+02
75	4.500E+03	8.456E-03	2.440E-05	1.623E+02	2.872E+02
76	4.560E+03	2.490E-02	7.186E-05	9.995E+01	2.249E+02
77	4.620E+03	1.035E-01	2.987E-04	-9.579E+01	2.911E+01
78	4.680E+03	2.426E-02	7.001E-05	1.625E+02	2.874E+02
79	4.740E+03	7.422E-02	2.142E-04	1.988E+00	1.269E+02
80	4.800E+03	1.657E-02	4.782E-05	-1.759E+02	-5.100E+01

TOTAL HARMONIC DISTORTION = 2.687360E+00 PERCENT

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(B_PH)

DC COMPONENT = 3.433933E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.465E+02	1.000E+00	1.151E+02	0.000E+00
2	1.200E+02	2.632E-01	7.597E-04	1.638E+02	4.870E+01
3	1.800E+02	7.920E-02	2.286E-04	-9.902E+01	-2.141E+02
4	2.400E+02	9.853E-02	2.844E-04	4.769E+01	-6.740E+01
5	3.000E+02	3.997E+00	1.153E-02	3.677E+01	-7.831E+01
6	3.600E+02	1.946E-01	5.616E-04	1.119E+02	-3.202E+00
7	4.200E+02	2.205E+00	6.364E-03	-9.938E+01	-2.145E+02
8	4.800E+02	1.358E-01	3.919E-04	-1.064E+02	-2.215E+02
9	5.400E+02	7.829E-02	2.259E-04	1.084E+02	-6.689E+00
10	6.000E+02	1.592E-01	4.593E-04	7.438E+01	-4.070E+01
11	6.600E+02	4.504E+00	1.300E-02	-1.760E+02	-2.911E+02
12	7.200E+02	1.497E-01	4.320E-04	-1.525E+02	-2.676E+02
13	7.800E+02	4.034E+00	1.164E-02	-1.276E+02	-2.427E+02
14	8.400E+02	9.387E-02	2.709E-04	6.579E+01	-4.929E+01
15	9.000E+02	2.602E-01	7.510E-04	1.218E+02	6.697E+00
16	9.600E+02	3.320E-01	9.581E-04	1.746E+02	5.948E+01
17	1.020E+03	1.849E+00	5.337E-03	1.582E+02	4.308E+01
18	1.080E+03	8.934E-01	2.578E-03	2.726E+01	-8.782E+01
19	1.140E+03	6.232E+00	1.799E-02	1.235E+01	-1.027E+02
20	1.200E+03	9.781E-01	2.823E-03	-7.235E+00	-1.223E+02
21	1.260E+03	1.033E+00	2.981E-03	2.952E+01	-8.556E+01
22	1.320E+03	6.111E-01	1.763E-03	6.226E+01	-5.282E+01
23	1.380E+03	1.887E+00	5.445E-03	1.406E+02	2.551E+01
24	1.440E+03	2.517E-01	7.263E-04	-1.267E+02	-2.418E+02
25	1.500E+03	8.359E-01	2.412E-03	-1.791E+02	-2.942E+02

26	1.560E+03	2.718E-01	7.843E-04	4.045E+01	-7.463E+01
27	1.620E+03	1.456E-01	4.201E-04	5.856E+01	-5.653E+01
28	1.680E+03	1.096E-01	3.164E-04	-9.137E+01	-2.065E+02
29	1.740E+03	1.703E-01	4.915E-04	9.902E+01	-1.606E+01
30	1.800E+03	2.827E-01	8.160E-04	3.690E+01	-7.818E+01
31	1.860E+03	2.452E-01	7.077E-04	3.361E+01	-8.148E+01
32	1.920E+03	9.448E-02	2.727E-04	-1.619E+02	-2.769E+02
33	1.980E+03	1.455E-01	4.199E-04	-1.039E+02	-2.189E+02
34	2.040E+03	6.396E-02	1.846E-04	7.270E+01	-4.238E+01
35	2.100E+03	6.864E-01	1.981E-03	2.589E+01	-8.919E+01
36	2.160E+03	1.387E-01	4.002E-04	-8.146E+00	-1.232E+02
37	2.220E+03	9.648E-01	2.784E-03	-8.276E+01	-1.978E+02
38	2.280E+03	6.969E-02	2.011E-04	-4.420E+01	-1.593E+02
39	2.340E+03	1.164E-01	3.360E-04	-4.797E+01	-1.631E+02
40	2.400E+03	5.435E-02	1.568E-04	8.332E+01	-3.177E+01
41	2.460E+03	1.372E-01	3.959E-04	-1.331E+02	-2.482E+02
42	2.520E+03	2.515E-02	7.258E-05	-5.033E+01	-1.654E+02
43	2.580E+03	4.615E-02	1.332E-04	1.108E+02	-4.313E+00
44	2.640E+03	8.750E-02	2.525E-04	2.631E+01	-8.877E+01
45	2.700E+03	4.951E-02	1.429E-04	7.138E+01	-4.370E+01
46	2.760E+03	3.808E-02	1.099E-04	4.247E+00	-1.108E+02
47	2.820E+03	2.145E-01	6.190E-04	-1.042E+01	-1.255E+02
48	2.880E+03	4.497E-02	1.298E-04	2.667E+01	-8.841E+01
49	2.940E+03	2.118E-01	6.113E-04	2.778E+01	-8.731E+01
50	3.000E+03	3.404E-02	9.823E-05	8.663E+01	-2.846E+01
51	3.060E+03	6.153E-02	1.776E-04	-4.717E+01	-1.623E+02
52	3.120E+03	4.830E-02	1.394E-04	7.922E+00	-1.072E+02
53	3.180E+03	1.049E-01	3.027E-04	-5.965E+01	-1.747E+02
54	3.240E+03	3.379E-02	9.752E-05	-1.585E+02	-2.735E+02
55	3.300E+03	1.500E-01	4.328E-04	1.473E+02	3.224E+01
56	3.360E+03	5.484E-02	1.583E-04	4.579E+01	-6.930E+01
57	3.420E+03	5.066E-02	1.462E-04	6.719E+01	-4.789E+01
58	3.480E+03	3.666E-02	1.058E-04	-7.348E+00	-1.224E+02
59	3.540E+03	9.749E-02	2.813E-04	1.434E+02	2.829E+01
60	3.600E+03	3.208E-02	9.258E-05	2.207E+01	-9.302E+01
61	3.660E+03	1.429E-01	4.125E-04	-1.798E+02	-2.949E+02
62	3.720E+03	4.597E-02	1.327E-04	-2.478E+01	-1.399E+02
63	3.780E+03	2.053E-02	5.924E-05	-5.222E+00	-1.203E+02
64	3.840E+03	1.308E-02	3.775E-05	-1.694E+02	-2.845E+02
65	3.900E+03	5.386E-02	1.554E-04	9.043E+01	-2.465E+01
66	3.960E+03	7.043E-02	2.033E-04	2.890E+01	-8.618E+01
67	4.020E+03	9.864E-02	2.847E-04	-2.498E+01	-1.401E+02

68	4.080E+03	2.867E-02	8.274E-05	-5.832E+01	-1.734E+02
69	4.140E+03	1.584E-02	4.570E-05	3.111E+01	-8.397E+01
70	4.200E+03	5.079E-02	1.466E-04	3.498E+01	-8.010E+01
71	4.260E+03	1.311E+00	3.783E-03	-1.156E+02	-2.307E+02
72	4.320E+03	3.686E-02	1.064E-04	-1.356E+02	-2.507E+02
73	4.380E+03	1.276E+00	3.681E-03	1.111E+02	-3.935E+00
74	4.440E+03	3.106E-02	8.965E-05	1.614E+01	-9.894E+01
75	4.500E+03	2.440E-02	7.042E-05	-1.125E+02	-2.276E+02
76	4.560E+03	1.279E-02	3.691E-05	-1.505E+02	-2.656E+02
77	4.620E+03	8.163E-02	2.356E-04	4.546E+01	-6.962E+01
78	4.680E+03	1.269E-02	3.663E-05	-1.280E+01	-1.279E+02
79	4.740E+03	4.285E-02	1.237E-04	-1.133E+02	-2.284E+02
80	4.800E+03	3.198E-02	9.229E-05	3.127E+01	-8.381E+01

TOTAL HARMONIC DISTORTION = 3.066368E+00 PERCENT

```
**** 07/26/95 10:28:56 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

 * C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

 ****     FOURIER ANALYSIS                    TEMPERATURE =   27.000 DEG C

******************************************************************************

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(C_PH)

 DC COMPONENT =   -2.793189E-01

 HARMONIC   FREQUENCY    FOURIER    NORMALIZED     PHASE        NORMALIZED
    NO         (HZ)     COMPONENT    COMPONENT     (DEG)       PHASE (DEG)

     1      6.000E+01   3.465E+02   1.000E+00   -4.900E+00     0.000E+00
     2      1.200E+02   3.293E-01   9.505E-04    4.387E+01     4.877E+01
     3      1.800E+02   6.578E-02   1.899E-04    1.001E+02     1.050E+02
     4      2.400E+02   3.871E-02   1.117E-04    1.641E+02     1.690E+02
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5	3.000E+02	3.957E+00	1.142E-02	1.573E+02	1.622E+02
6	3.600E+02	3.721E-02	1.074E-04	-3.047E+01	-2.557E+01
7	4.200E+02	2.145E+00	6.190E-03	1.422E+02	1.471E+02
8	4.800E+02	8.929E-02	2.577E-04	1.226E+02	1.275E+02
9	5.400E+02	8.205E-02	2.368E-04	-7.615E+01	-7.125E+01
10	6.000E+02	6.819E-02	1.968E-04	-1.089E+02	-1.040E+02
11	6.600E+02	4.492E+00	1.296E-02	-5.410E+01	-4.920E+01
12	7.200E+02	7.978E-02	2.303E-04	8.930E+01	9.420E+01
13	7.800E+02	3.875E+00	1.118E-02	1.104E+02	1.153E+02
14	8.400E+02	1.602E-01	4.624E-04	1.414E+02	1.463E+02
15	9.000E+02	1.683E-01	4.857E-04	-9.894E+00	-4.993E+00
16	9.600E+02	1.354E-01	3.909E-04	4.880E+01	5.370E+01
17	1.020E+03	1.496E+00	4.318E-03	-8.515E+01	-8.025E+01
18	1.080E+03	6.384E-01	1.843E-03	-1.661E+02	-1.612E+02
19	1.140E+03	6.313E+00	1.822E-02	-1.343E+02	-1.294E+02
20	1.200E+03	1.133E+00	3.272E-03	-1.057E+01	-5.673E+00
21	1.260E+03	3.837E-01	1.107E-03	1.399E+02	1.448E+02
22	1.320E+03	1.576E-01	4.548E-04	-7.306E+01	-6.816E+01
23	1.380E+03	1.743E+00	5.032E-03	-1.104E+02	-1.055E+02
24	1.440E+03	1.216E-01	3.511E-04	-1.409E+01	-9.190E+00
25	1.500E+03	7.476E-01	2.158E-03	5.846E+01	6.336E+01
26	1.560E+03	1.965E-01	5.673E-04	-1.203E+02	-1.154E+02
27	1.620E+03	2.942E-01	8.491E-04	-8.152E+01	-7.662E+01
28	1.680E+03	9.607E-02	2.773E-04	-1.368E+01	-8.778E+00
29	1.740E+03	3.764E-01	1.086E-03	-1.006E+02	-9.574E+01
30	1.800E+03	5.660E-02	1.634E-04	-1.656E+02	-1.607E+02
31	1.860E+03	2.400E-01	6.926E-04	-1.280E+02	-1.231E+02
32	1.920E+03	7.101E-02	2.050E-04	1.279E+02	1.328E+02
33	1.980E+03	5.519E-02	1.593E-04	1.081E+02	1.130E+02
34	2.040E+03	1.466E-01	4.230E-04	-1.394E+02	-1.345E+02
35	2.100E+03	5.684E-01	1.641E-03	1.461E+02	1.510E+02
36	2.160E+03	1.085E-01	3.131E-04	-1.467E+02	-1.418E+02
37	2.220E+03	1.016E+00	2.933E-03	1.489E+02	1.538E+02
38	2.280E+03	4.593E-02	1.326E-04	9.219E+01	9.709E+01
39	2.340E+03	1.138E-01	3.286E-04	1.150E+02	1.199E+02
40	2.400E+03	5.093E-02	1.470E-04	-9.732E+01	-9.242E+01
41	2.460E+03	1.249E-01	3.606E-04	8.061E+00	1.296E+01
42	2.520E+03	4.317E-02	1.246E-04	-7.923E+01	-7.433E+01
43	2.580E+03	1.288E-01	3.718E-04	-3.405E+00	1.496E+00
44	2.640E+03	3.837E-02	1.107E-04	-1.003E+02	-9.538E+01
45	2.700E+03	5.721E-02	1.651E-04	-3.546E+01	-3.056E+01
46	2.760E+03	1.498E-02	4.323E-05	-8.828E+01	-8.338E+01

47	2.820E+03	1.952E-01	5.634E-04	1.151E+02	1.200E+02
48	2.880E+03	2.743E-02	7.916E-05	-1.645E+02	-1.596E+02
49	2.940E+03	1.434E-01	4.140E-04	-1.039E+02	-9.905E+01
50	3.000E+03	5.286E-02	1.526E-04	-9.852E+01	-9.362E+01
51	3.060E+03	4.799E-02	1.385E-04	1.192E+02	1.241E+02
52	3.120E+03	5.886E-02	1.699E-04	-1.777E+02	-1.728E+02
53	3.180E+03	7.547E-02	2.178E-04	8.058E+01	8.548E+01
54	3.240E+03	2.812E-02	8.115E-05	-5.936E+01	-5.446E+01
55	3.300E+03	1.480E-01	4.271E-04	7.950E-01	5.695E+00
56	3.360E+03	4.965E-02	1.433E-04	-1.677E+02	-1.628E+02
57	3.420E+03	2.165E-02	6.247E-05	-1.263E+02	-1.214E+02
58	3.480E+03	2.819E-02	8.136E-05	-1.556E+02	-1.507E+02
59	3.540E+03	1.250E-01	3.608E-04	-1.007E+02	-9.577E+01
60	3.600E+03	3.223E-02	9.304E-05	-1.460E+02	-1.411E+02
61	3.660E+03	1.328E-01	3.834E-04	4.650E+01	5.140E+01
62	3.720E+03	1.346E-02	3.886E-05	-1.581E+02	-1.532E+02
63	3.780E+03	3.625E-02	1.046E-04	-9.744E+01	-9.254E+01
64	3.840E+03	2.334E-02	6.737E-05	4.207E+00	9.107E+00
65	3.900E+03	6.988E-02	2.017E-04	-1.265E+02	-1.216E+02
66	3.960E+03	2.157E-02	6.227E-05	-1.649E+02	-1.600E+02
67	4.020E+03	8.316E-02	2.400E-04	-1.610E+02	-1.561E+02
68	4.080E+03	3.373E-02	9.736E-05	1.051E+02	1.100E+02
69	4.140E+03	7.642E-03	2.206E-05	1.316E+02	1.365E+02
70	4.200E+03	3.617E-02	1.044E-04	1.574E+02	1.623E+02
71	4.260E+03	1.307E+00	3.772E-03	3.389E+00	8.290E+00
72	4.320E+03	1.102E-02	3.180E-05	9.960E+01	1.045E+02
73	4.380E+03	1.289E+00	3.720E-03	-6.896E+00	-1.996E+00
74	4.440E+03	1.541E-02	4.448E-05	-1.098E+02	-1.049E+02
75	4.500E+03	2.648E-02	7.643E-05	4.892E+01	5.382E+01
76	4.560E+03	2.389E-02	6.895E-05	-4.975E+01	-4.485E+01
77	4.620E+03	6.481E-02	1.871E-04	1.363E+02	1.412E+02
78	4.680E+03	1.166E-02	3.365E-05	-2.265E+01	-1.775E+01
79	4.740E+03	6.800E-02	1.963E-04	1.473E+02	1.522E+02
80	4.800E+03	1.883E-02	5.434E-05	-1.250E+02	-1.201E+02

TOTAL HARMONIC DISTORTION = 3.007150E+00 PERCENT

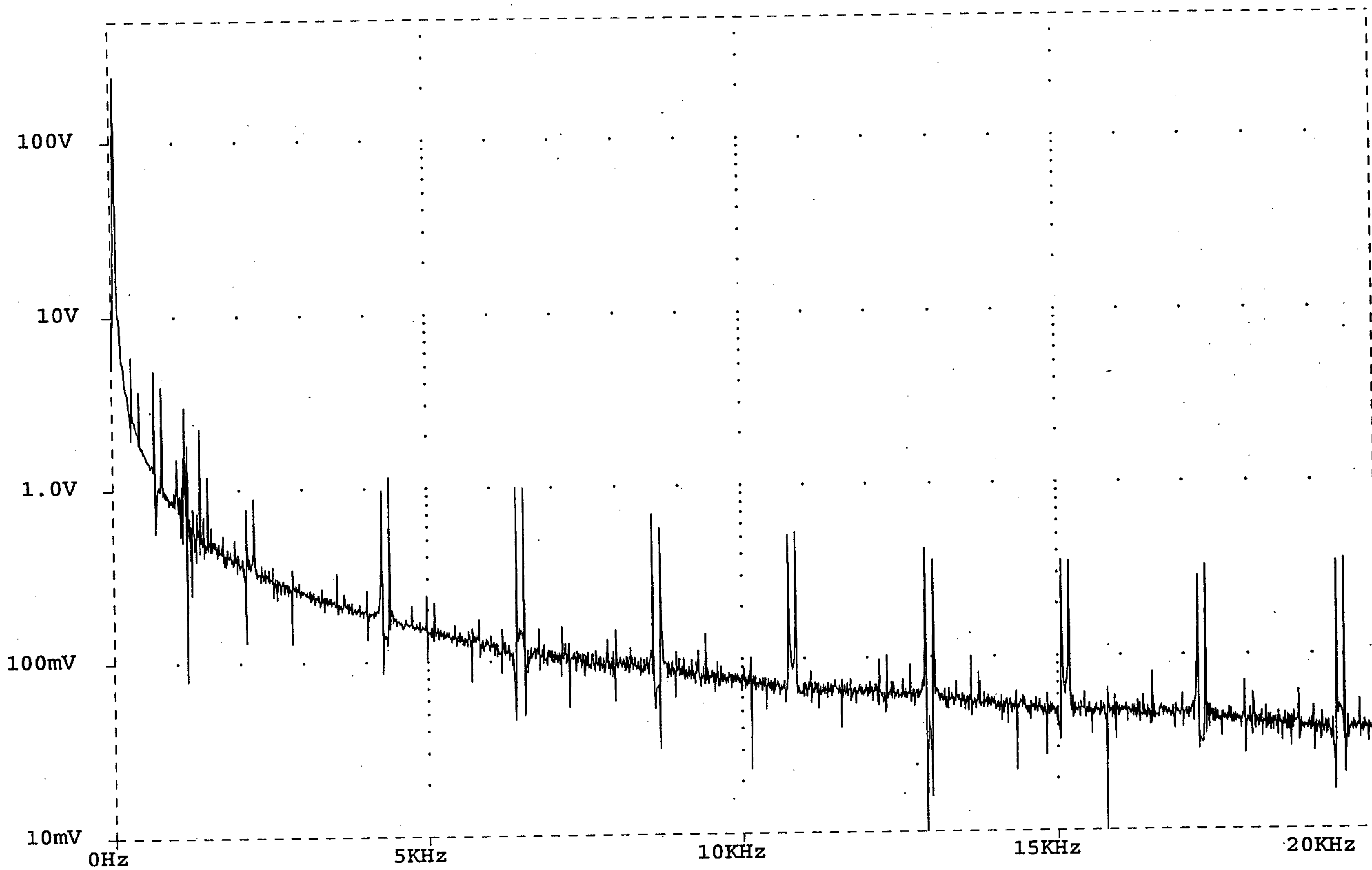
JOB CONCLUDED

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/26/95 10:28:56

Temperature: 27.0

(G) A Phase Output Voltage FFT - expanded



Date: July 26, 1995

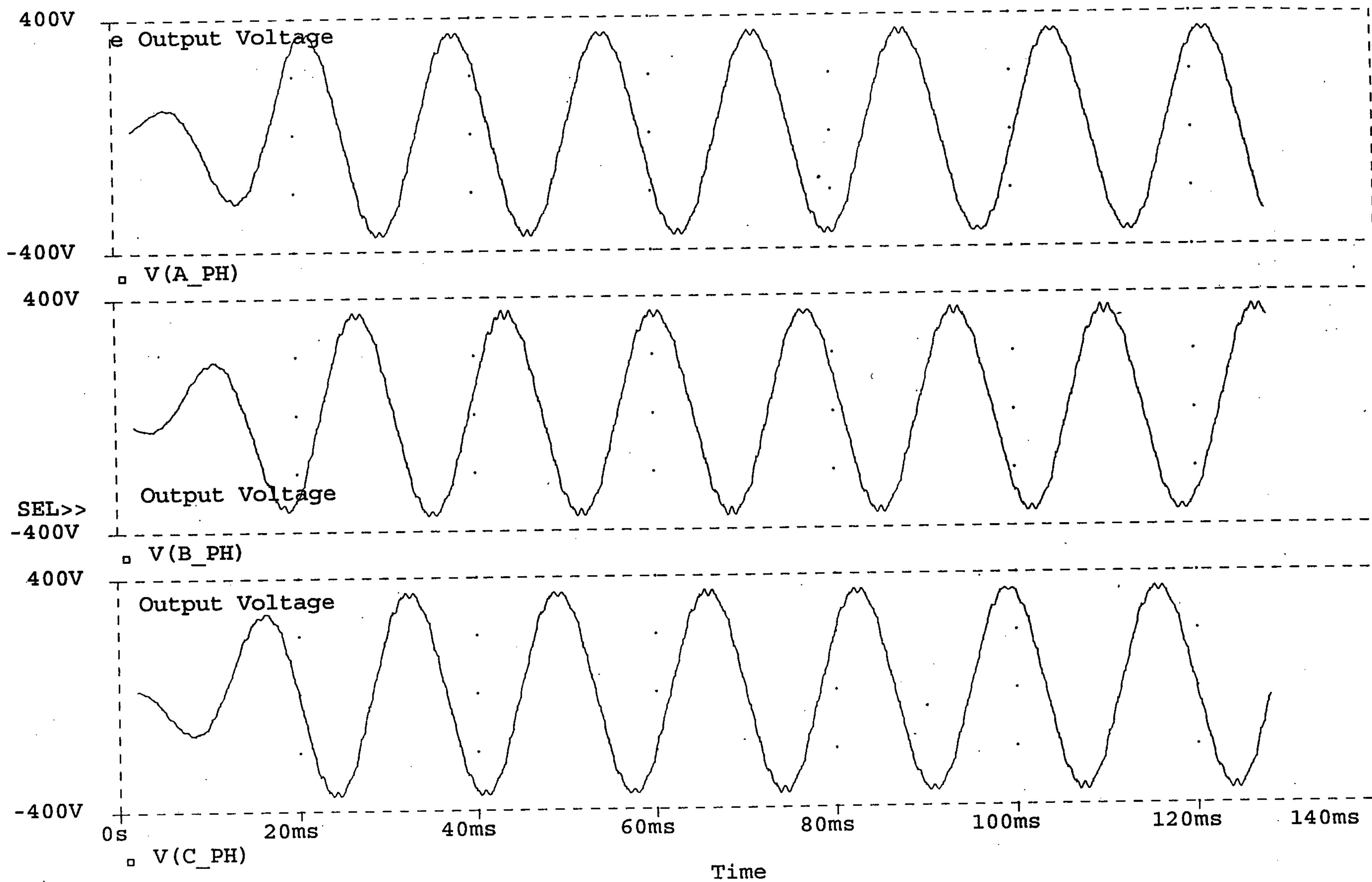
Page 1

Time: 11:30:27

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

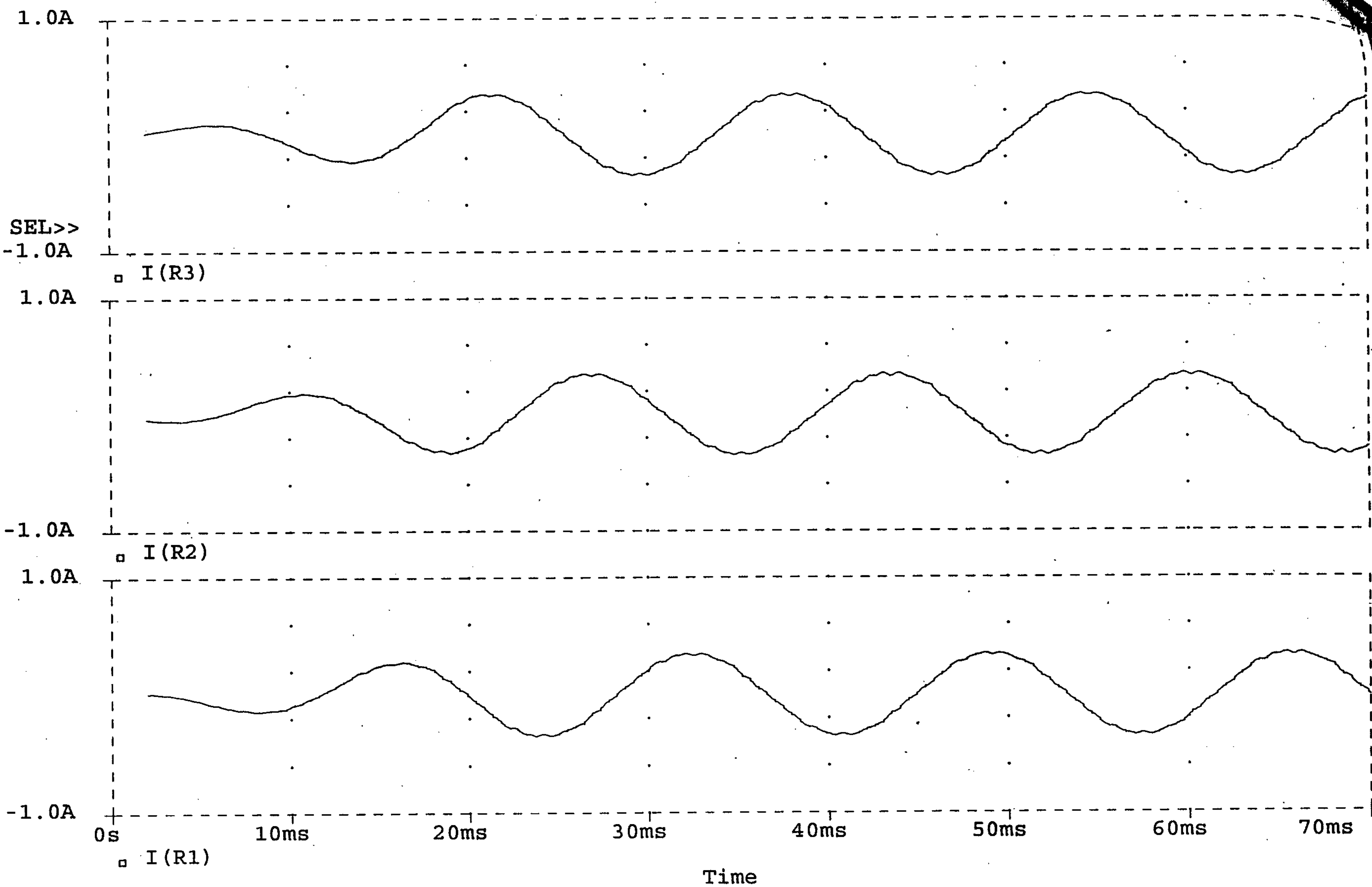
Date/Time run: 07/26/95 10:28:56 Temperature: 27.0

(A) 3 Phase Output Voltages (l-n)



* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH
Date/Time run: 07/26/95 10:28:56 Temperature: 2[illegible]

(C) 3 Phase Output Currents

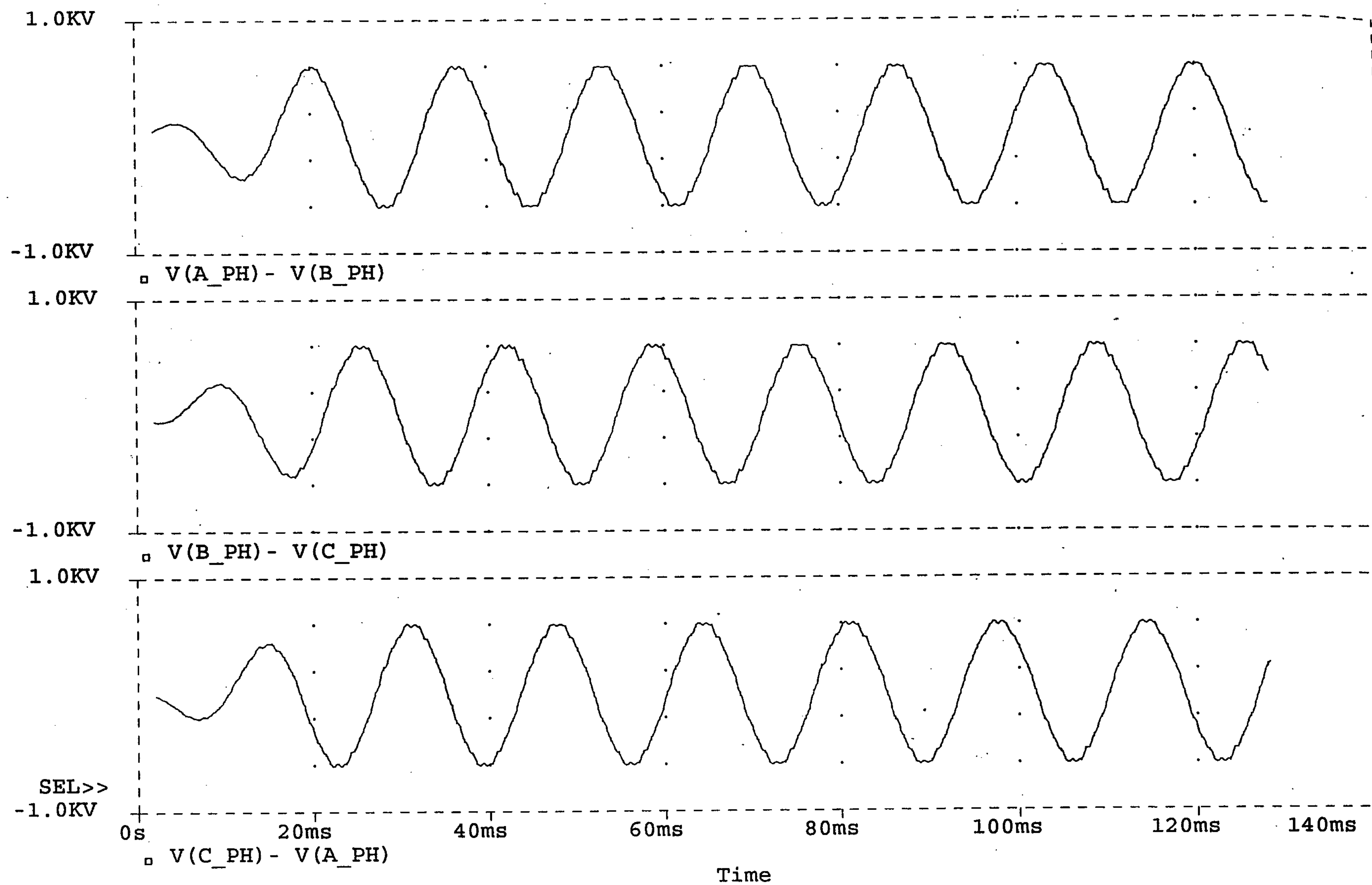


Date: July 26, 1995 Page 1 Time: 11:13:17

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/26/95 10:28:56 Temperature: 27.0

(D) 3 Phase Output Voltages (1-1)



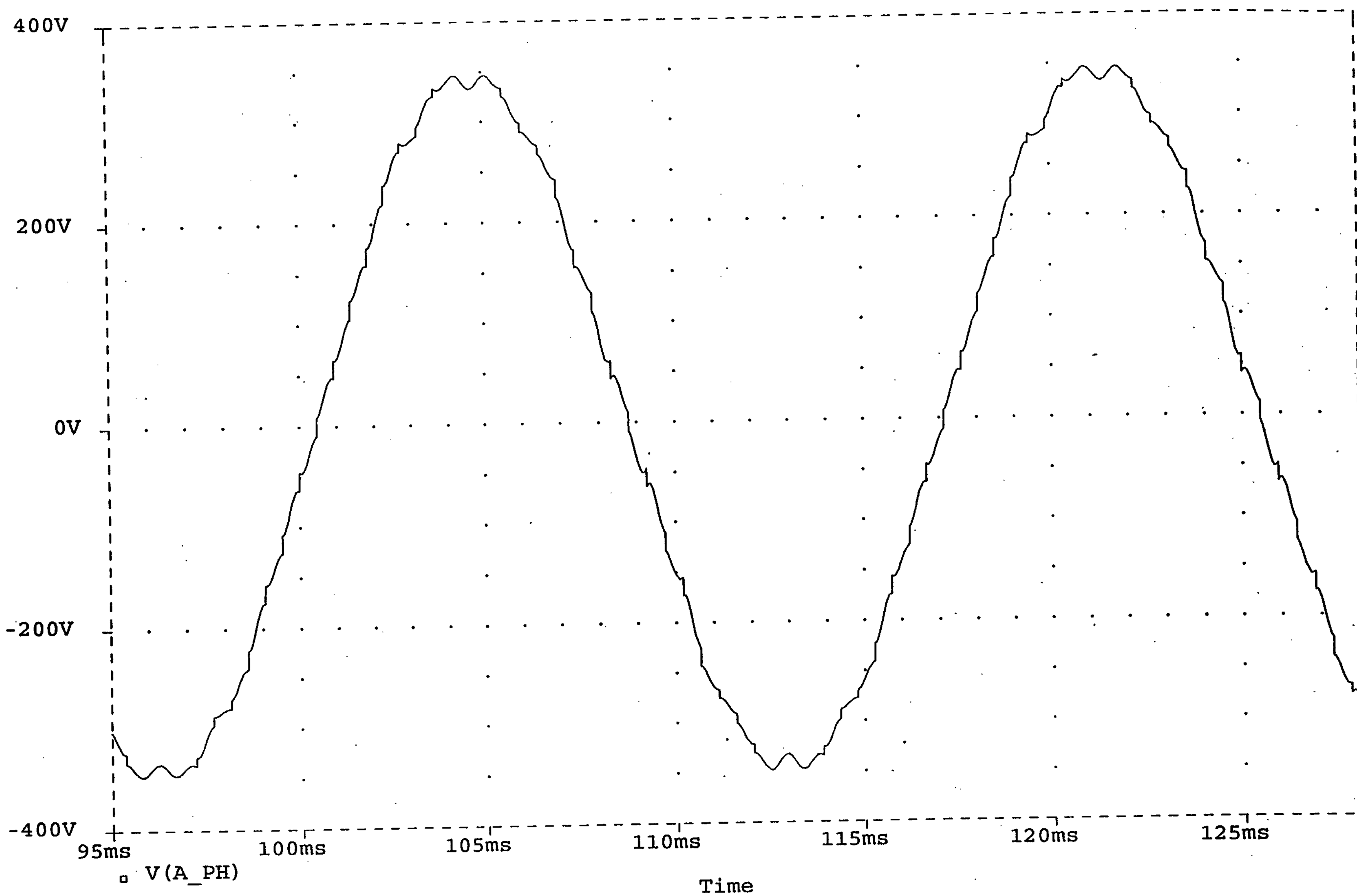
Date: July 26, 1995 Page 4 Time: 11:16:46

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/26/95 10:28:56

Temperature: 27.0

(E) A Phase Output Voltage - expanded



Date: July 26, 1995

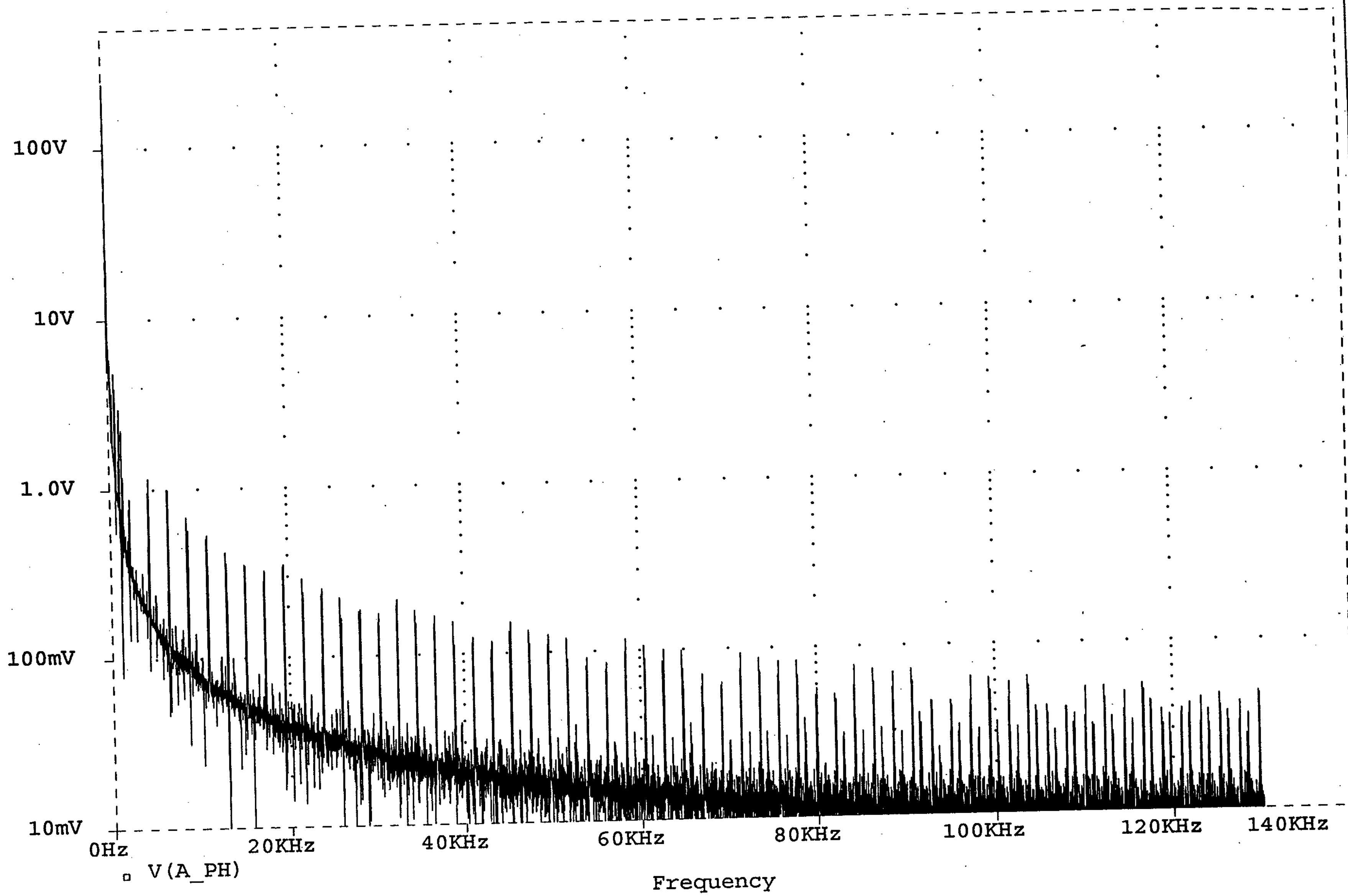
Time: 11:17:48

* C:\DATA\PSPICE\3PH60HZ\BATCH\3PH-B11.SCH

Date/Time run: 07/26/95 10:28:56

Temperature: 27.0

(F) A Phase Output Voltage FFT



Date: July 26, 1995

Time: 11:18:04

Simulation Results

6 Bridge Configuration

Unfiltered Output

$R_L = 1.728\ \Omega$

$P_{OUT} = 100$ kW

* Using only output transformer leakage inductance

**** 07/20/95 17:51:44 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(A_PH)

DC COMPONENT = -4.768017E-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.369E+02	1.000E+00	-1.328E+02	0.000E+00
2	1.200E+02	9.883E-01	2.933E-03	-7.028E+01	6.250E+01
3	1.800E+02	8.863E-02	2.631E-04	7.784E+01	2.106E+02
4	2.400E+02	1.845E-01	5.477E-04	5.190E+01	1.847E+02
5	3.000E+02	3.175E+00	9.423E-03	-1.203E+02	1.245E+01
6	3.600E+02	1.212E-01	3.599E-04	-1.452E+02	-1.240E+01
7	4.200E+02	1.489E+00	4.418E-03	-2.214E+01	1.106E+02
8	4.800E+02	7.576E-02	2.249E-04	1.180E+01	1.446E+02
9	5.400E+02	4.359E-02	1.294E-04	1.239E+02	2.566E+02
10	6.000E+02	2.047E-01	6.075E-04	-1.729E+02	-4.010E+01
11	6.600E+02	1.492E+00	4.428E-03	9.650E+00	1.424E+02
12	7.200E+02	7.666E-02	2.275E-04	-1.707E+02	-3.787E+01
13	7.800E+02	1.404E+00	4.166E-03	-6.792E+01	6.486E+01
14	8.400E+02	2.182E-01	6.477E-04	-9.977E+01	3.301E+01
15	9.000E+02	3.741E-02	1.110E-04	1.341E+02	2.669E+02
16	9.600E+02	8.892E-02	2.639E-04	1.178E+01	1.446E+02
17	1.020E+03	2.038E-01	6.050E-04	-5.815E+01	7.463E+01
18	1.080E+03	5.838E-02	1.733E-04	1.569E+02	2.897E+02
19	1.140E+03	1.663E-01	4.937E-04	5.363E+01	1.864E+02
20	1.200E+03	7.816E-02	2.320E-04	-1.513E+02	-1.856E+01
21	1.260E+03	5.462E-02	1.621E-04	1.541E+02	2.869E+02
22	1.320E+03	9.139E-02	2.713E-04	-4.580E+01	8.698E+01
23	1.380E+03	2.827E-01	8.390E-04	1.072E+02	2.399E+02
24	1.440E+03	1.289E-02	3.827E-05	1.635E+02	2.963E+02
25	1.500E+03	4.986E-01	1.480E-03	4.976E+01	1.825E+02
26	1.560E+03	7.413E-02	2.200E-04	6.954E+01	2.023E+02
27	1.620E+03	5.746E-02	1.705E-04	-1.648E+02	-3.204E+01
28	1.680E+03	6.719E-02	1.994E-04	-1.251E+02	7.639E+00
29	1.740E+03	7.073E-02	2.099E-04	9.572E+01	2.285E+02
30	1.800E+03	1.512E-02	4.489E-05	7.398E+01	2.068E+02
31	1.860E+03	1.538E-01	4.565E-04	-1.604E+02	-2.760E+01
32	1.920E+03	7.004E-02	2.079E-04	-1.392E+02	-6.436E+00

33	1.980E+03	4.180E-02	1.241E-04	-1.328E+02	-3.422E-04
34	2.040E+03	1.068E-01	3.170E-04	-2.033E+01	1.125E+02
35	2.100E+03	1.869E+00	5.546E-03	-1.258E+02	7.021E+00
36	2.160E+03	1.396E-02	4.142E-05	-1.464E+02	-1.363E+01
37	2.220E+03	1.636E+00	4.857E-03	-1.558E+01	1.172E+02
38	2.280E+03	9.697E-02	2.878E-04	6.078E+01	1.936E+02
39	2.340E+03	5.040E-02	1.496E-04	-1.446E+02	-1.182E+01
40	2.400E+03	5.536E-02	1.643E-04	-1.582E+02	-2.544E+01
41	2.460E+03	6.916E-02	2.053E-04	1.490E+01	1.477E+02
42	2.520E+03	1.820E-02	5.403E-05	-5.714E+01	7.564E+01
43	2.580E+03	7.238E-02	2.148E-04	1.431E+02	2.758E+02
44	2.640E+03	5.035E-02	1.494E-04	1.770E+02	3.098E+02
45	2.700E+03	1.558E-02	4.624E-05	-1.506E+02	-1.786E+01
46	2.760E+03	6.148E-02	1.825E-04	-6.796E+01	6.482E+01
47	2.820E+03	9.728E-02	2.888E-04	-1.696E+02	-3.687E+01
48	2.880E+03	2.932E-02	8.703E-05	-9.667E+01	3.611E+01
49	2.940E+03	1.273E-01	3.778E-04	9.750E+01	2.303E+02
50	3.000E+03	2.351E-02	6.978E-05	8.763E+01	2.204E+02

TOTAL HARMONIC DISTORTION = 1.464459E+00 PERCENT

**** 07/20/95 17:51:44 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

****   FOURIER ANALYSIS   TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(B_PH)

DC COMPONENT = -1.916154E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.370E+02	1.000E+00	1.072E+02	0.000E+00
2	1.200E+02	7.484E-01	2.221E-03	1.576E+02	5.038E+01
3	1.800E+02	9.036E-02	2.682E-04	-8.437E+01	-1.916E+02
4	2.400E+02	1.732E-01	5.141E-04	-1.028E+02	-2.100E+02
5	3.000E+02	3.097E+00	9.190E-03	4.639E-01	-1.067E+02
6	3.600E+02	1.311E-01	3.892E-04	4.373E+01	-6.346E+01
7	4.200E+02	1.433E+00	4.253E-03	-1.402E+02	-2.474E+02
8	4.800E+02	7.888E-02	2.341E-04	-1.491E+02	-2.563E+02
9	5.400E+02	7.038E-02	2.089E-04	-1.032E+02	-2.104E+02
10	6.000E+02	1.787E-01	5.304E-04	-5.032E+01	-1.575E+02
11	6.600E+02	1.596E+00	4.737E-03	1.314E+02	2.422E+01
12	7.200E+02	2.276E-01	6.755E-04	-1.323E+02	-2.395E+02
13	7.800E+02	1.376E+00	4.085E-03	1.719E+02	6.475E+01
14	8.400E+02	1.106E-01	3.283E-04	1.033E+02	-3.855E+00
15	9.000E+02	3.607E-02	1.070E-04	-1.028E+02	-2.100E+02
16	9.600E+02	8.203E-02	2.434E-04	-1.333E+02	-2.405E+02
17	1.020E+03	2.030E-01	6.026E-04	8.022E+01	-2.698E+01
18	1.080E+03	2.578E-02	7.649E-05	-4.899E+01	-1.562E+02
19	1.140E+03	1.372E-01	4.072E-04	-6.876E+01	-1.760E+02
20	1.200E+03	2.176E-02	6.457E-05	-6.994E+01	-1.771E+02
21	1.260E+03	2.839E-02	8.425E-05	-4.297E+01	-1.502E+02
22	1.320E+03	8.230E-02	2.442E-04	1.357E+02	2.845E+01
23	1.380E+03	3.282E-01	9.741E-04	-1.411E+02	-2.483E+02
24	1.440E+03	1.171E-01	3.476E-04	9.815E+00	-9.738E+01
25	1.500E+03	5.087E-01	1.510E-03	-7.352E+01	-1.807E+02
26	1.560E+03	1.088E-01	3.230E-04	-8.750E+01	-1.947E+02
27	1.620E+03	9.736E-03	2.889E-05	-4.391E+01	-1.511E+02
28	1.680E+03	3.768E-02	1.118E-04	7.524E+01	-3.195E+01
29	1.740E+03	1.297E-01	3.848E-04	-1.550E+02	-2.622E+02
30	1.800E+03	6.041E-02	1.793E-04	-1.228E+02	-2.300E+02
31	1.860E+03	1.200E-01	3.561E-04	7.192E+01	-3.528E+01
32	1.920E+03	1.963E-02	5.827E-05	6.337E+01	-4.383E+01

33	1.980E+03	2.256E-02	6.694E-05	-1.244E+02	-2.316E+02
34	2.040E+03	7.342E-02	2.179E-04	1.290E+02	2.178E+01
35	2.100E+03	1.817E+00	5.392E-03	-6.554E+00	-1.138E+02
36	2.160E+03	1.490E-01	4.422E-04	1.900E+01	-8.820E+01
37	2.220E+03	1.683E+00	4.993E-03	-1.357E+02	-2.429E+02
38	2.280E+03	9.126E-02	2.708E-04	-8.486E+01	-1.921E+02
39	2.340E+03	7.669E-03	2.276E-05	8.759E+01	-1.961E+01
40	2.400E+03	1.299E-02	3.854E-05	2.723E+01	-7.997E+01
41	2.460E+03	8.649E-02	2.567E-04	1.561E+02	4.889E+01
42	2.520E+03	2.666E-02	7.910E-05	-1.763E+02	-2.835E+02
43	2.580E+03	3.410E-02	1.012E-04	1.147E+01	-9.573E+01
44	2.640E+03	4.414E-02	1.310E-04	-6.741E+01	-1.746E+02
45	2.700E+03	1.729E-02	5.131E-05	1.531E+02	4.586E+01
46	2.760E+03	6.314E-02	1.874E-04	1.233E+02	1.609E+01
47	2.820E+03	9.576E-02	2.842E-04	-4.415E+01	-1.514E+02
48	2.880E+03	5.106E-02	1.515E-04	2.146E+01	-8.574E+01
49	2.940E+03	1.256E-01	3.727E-04	-4.235E+01	-1.496E+02
50	3.000E+03	4.567E-02	1.355E-04	-9.143E+01	-1.986E+02

TOTAL HARMONIC DISTORTION = 1.439515E+00 PERCENT

**** 07/20/95 17:51:44 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

****   FOURIER ANALYSIS   TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(C_PH)

DC COMPONENT = 2.392967E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.368E+02	1.000E+00	-1.280E+01	0.000E+00
2	1.200E+02	7.378E-01	2.190E-03	6.094E+01	7.374E+01
3	1.800E+02	2.773E-02	8.233E-05	1.732E+02	1.860E+02
4	2.400E+02	7.908E-02	2.348E-04	1.626E+02	1.754E+02
5	3.000E+02	3.099E+00	9.200E-03	1.188E+02	1.316E+02
6	3.600E+02	2.196E-02	6.518E-05	-7.745E+01	-6.465E+01
7	4.200E+02	1.505E+00	4.468E-03	1.006E+02	1.134E+02
8	4.800E+02	2.583E-02	7.668E-05	1.045E+02	1.173E+02
9	5.400E+02	5.173E-02	1.536E-04	3.867E+01	5.147E+01
10	6.000E+02	1.856E-01	5.511E-04	6.136E+01	7.416E+01
11	6.600E+02	1.505E+00	4.469E-03	-1.060E+02	-9.320E+01
12	7.200E+02	2.917E-01	8.659E-04	3.829E+01	5.109E+01
13	7.800E+02	1.387E+00	4.119E-03	5.298E+01	6.578E+01
14	8.400E+02	1.243E-01	3.691E-04	5.979E+01	7.259E+01
15	9.000E+02	3.504E-02	1.040E-04	1.371E+01	2.651E+01
16	9.600E+02	5.172E-02	1.536E-04	1.266E+02	1.393E+02
17	1.020E+03	1.446E-01	4.293E-04	-1.693E+02	-1.565E+02
18	1.080E+03	3.695E-02	1.097E-04	-5.372E+00	7.427E+00
19	1.140E+03	1.485E-01	4.407E-04	-1.777E+02	-1.649E+02
20	1.200E+03	8.421E-02	2.500E-04	4.346E+01	5.626E+01
21	1.260E+03	2.872E-02	8.526E-05	-9.009E+00	3.790E+00
22	1.320E+03	9.357E-03	2.778E-05	1.213E+02	1.341E+02
23	1.380E+03	3.447E-01	1.023E-03	-1.068E+01	2.124E+00
24	1.440E+03	1.057E-01	3.139E-04	-1.671E+02	-1.543E+02
25	1.500E+03	4.786E-01	1.421E-03	1.671E+02	1.799E+02
26	1.560E+03	4.984E-02	1.480E-04	1.280E+02	1.408E+02
27	1.620E+03	5.312E-02	1.577E-04	2.423E+01	3.703E+01
28	1.680E+03	3.447E-02	1.023E-04	3.248E+01	4.527E+01
29	1.740E+03	1.256E-01	3.728E-04	-7.135E+00	5.664E+00
30	1.800E+03	4.614E-02	1.370E-04	5.180E+01	6.460E+01
31	1.860E+03	1.244E-01	3.694E-04	-3.012E+01	-1.732E+01
32	1.920E+03	5.246E-02	1.557E-04	3.252E+01	4.532E+01

33	1.980E+03	6.420E-02	1.906E-04	5.015E+01	6.294E+01
34	2.040E+03	5.756E-02	1.709E-04	-1.597E+02	-1.469E+02
35	2.100E+03	1.865E+00	5.538E-03	1.125E+02	1.253E+02
36	2.160E+03	1.355E-01	4.024E-04	-1.625E+02	-1.497E+02
37	2.220E+03	1.658E+00	4.921E-03	1.030E+02	1.158E+02
38	2.280E+03	5.586E-02	1.658E-04	1.736E+02	1.864E+02
39	2.340E+03	4.610E-02	1.368E-04	2.785E+01	4.064E+01
40	2.400E+03	4.245E-02	1.260E-04	2.012E+01	3.291E+01
41	2.460E+03	5.423E-02	1.610E-04	-7.697E+01	-6.417E+01
42	2.520E+03	2.384E-02	7.079E-05	4.546E+01	5.826E+01
43	2.580E+03	5.590E-02	1.659E-04	-6.409E+01	-5.129E+01
44	2.640E+03	5.063E-02	1.503E-04	4.883E+01	6.163E+01
45	2.700E+03	2.899E-02	8.608E-05	-3.811E-01	1.242E+01
46	2.760E+03	1.233E-02	3.661E-05	1.996E+01	3.276E+01
47	2.820E+03	8.841E-02	2.625E-04	7.222E+01	8.502E+01
48	2.880E+03	4.533E-02	1.346E-04	1.667E+02	1.795E+02
49	2.940E+03	8.681E-02	2.577E-04	-1.514E+02	-1.386E+02
50	3.000E+03	2.217E-02	6.582E-05	8.957E+01	1.024E+02

TOTAL HARMONIC DISTORTION = 1.439029E+00 PERCENT

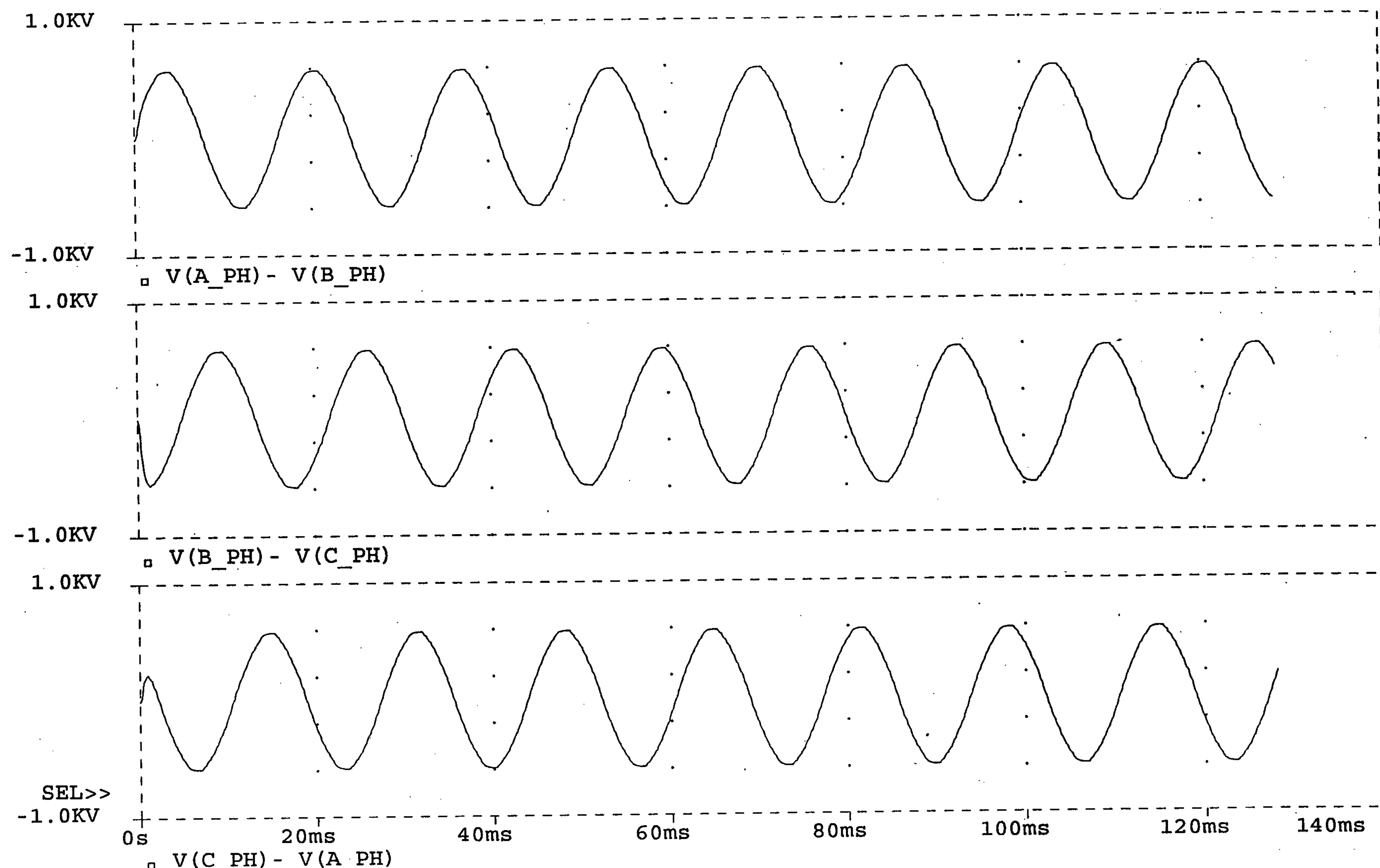
JOB CONCLUDED

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/20/95 17:51:44

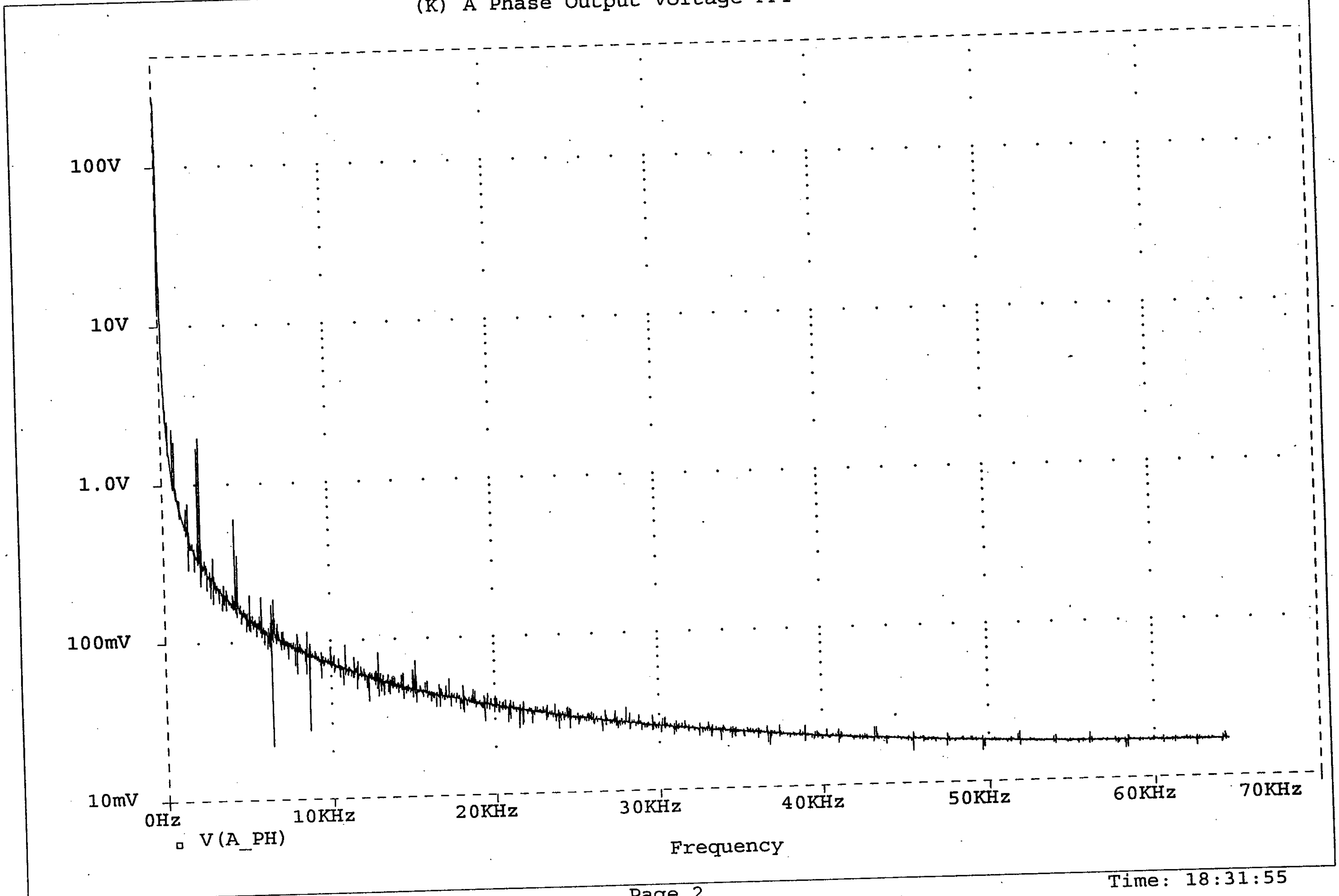
Temperature: 27.0

(M) 3 Phase Output Voltages (1-1)



Date/Time run: 07/20/95 17:51:44 * C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH Temperature: 27.0

(K) A Phase Output Voltage FFT



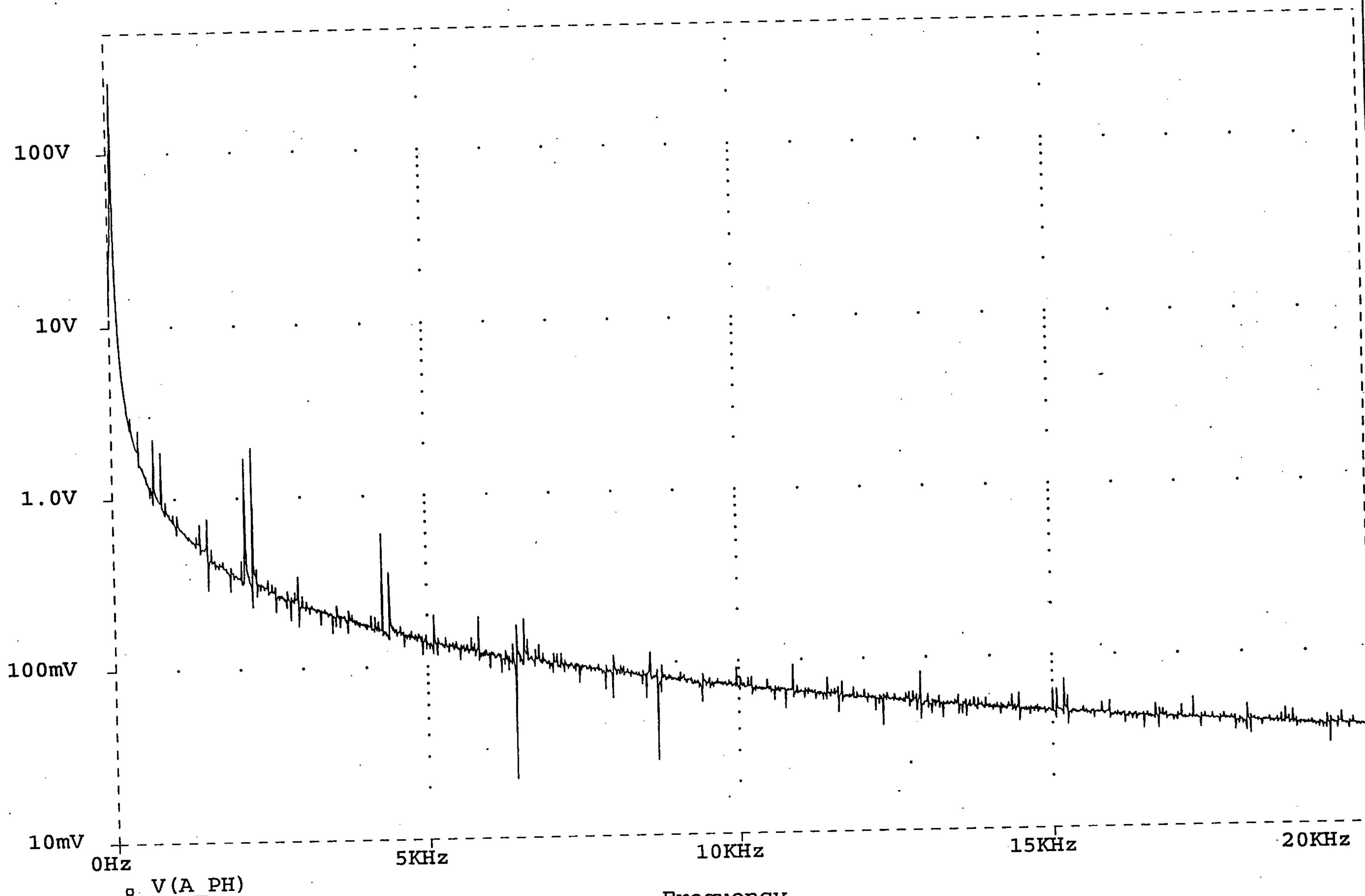
Date: July 20, 1995 Page 2 Time: 18:31:55

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/20/95 17:51:44

Temperature: 27.0

(J) A Phase Output Voltage FFT - expanded



Date: July 20, 1995

Page 3

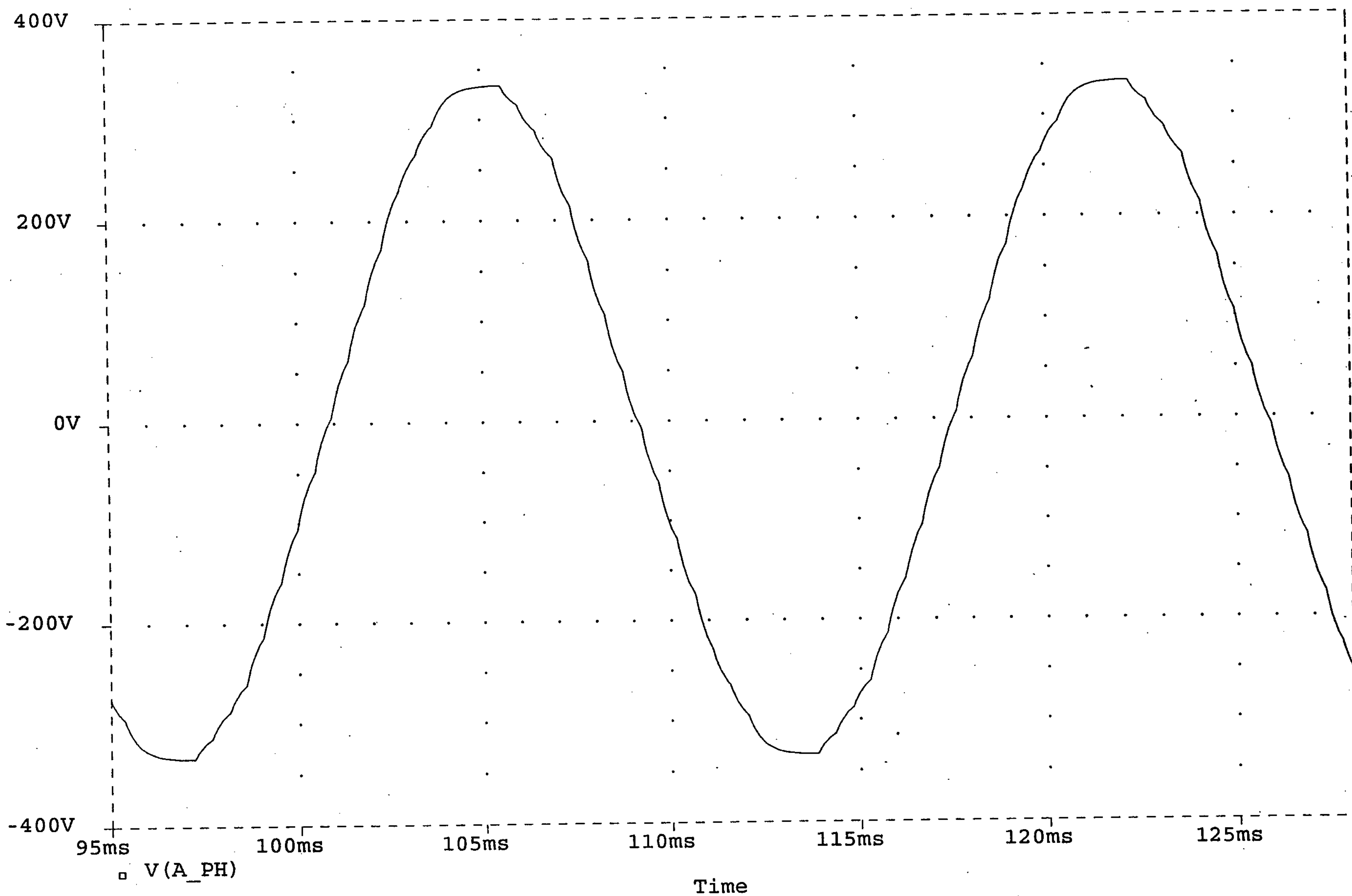
Time: 18:33:14

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/20/95 17:51:44

Temperature: 27.0

(I) A Phase Output Voltage - expanded



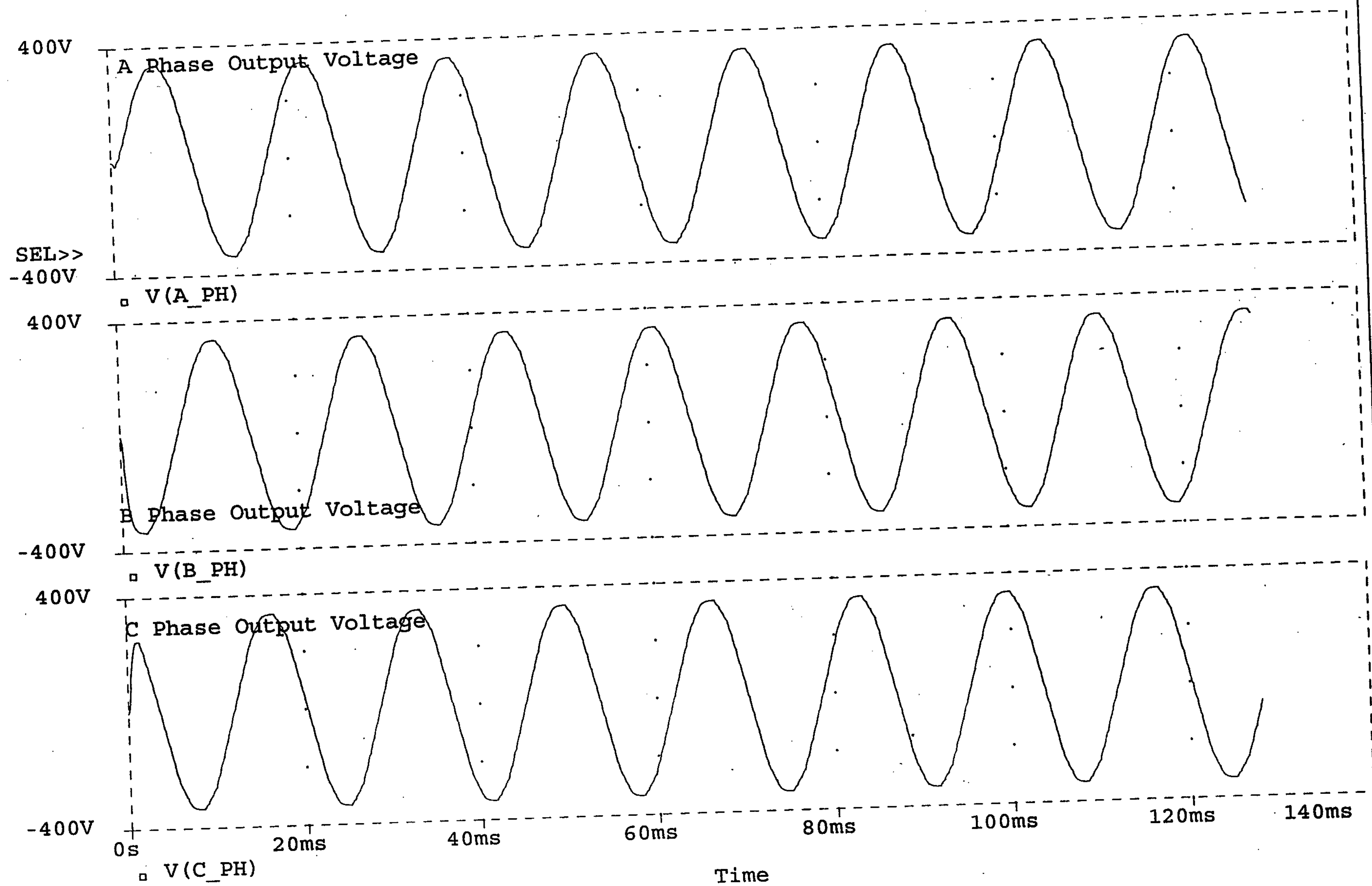
Date: July 20, 1995

Time: 18:33:55

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/20/95 17:51:44 Temperature: 27.0

(H) 3 Phase Output Voltages (l-n)

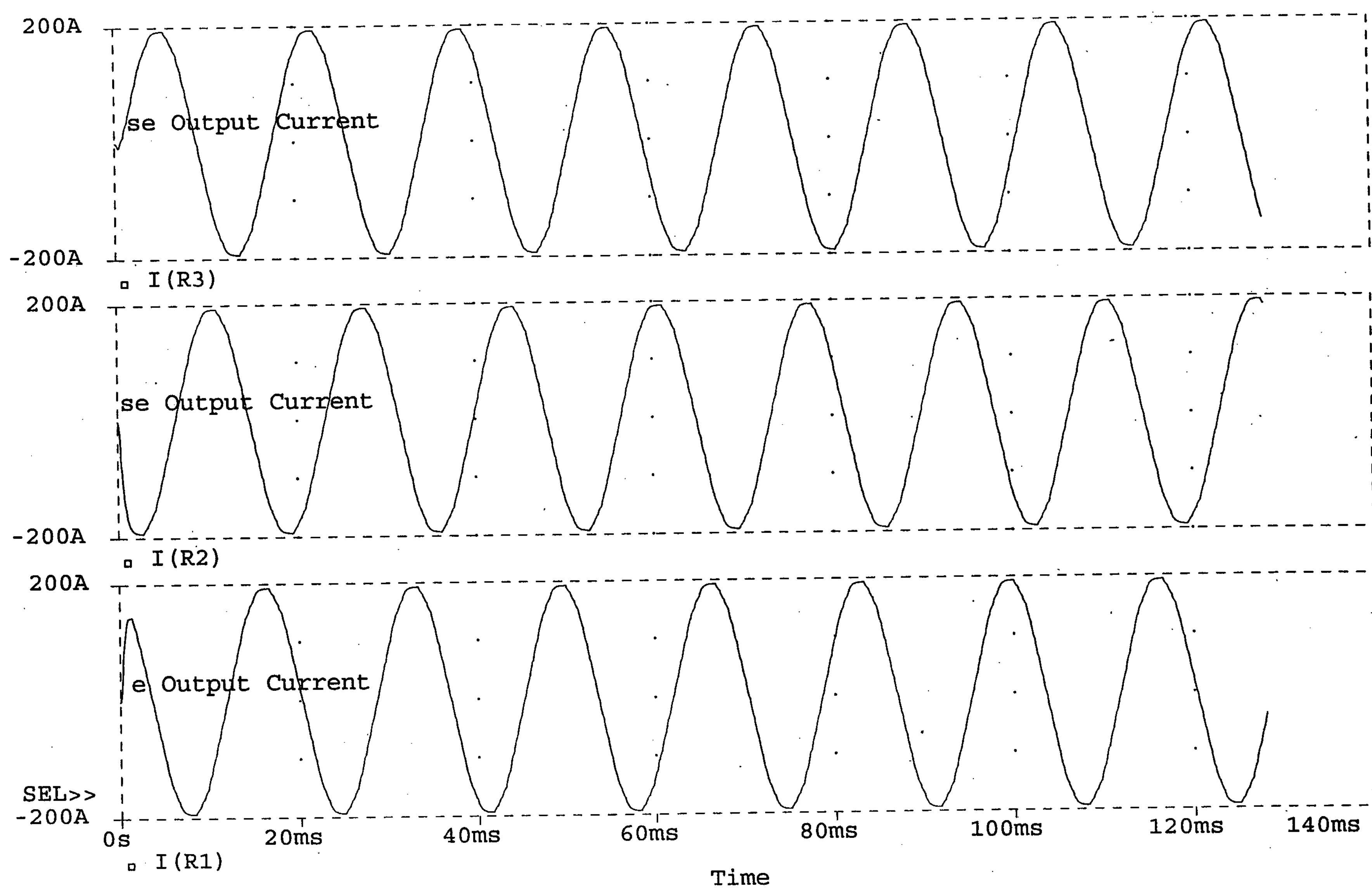


Date: July 20, 1995 Time: 18:34:29

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/20/95 17:51:44 Temperature: 27.0

(L) 3 Phase Output Currents



Date: July 20, 1995 Page 6 Time: 18:35:44

Simulation Results

6 Bridge Configuration

Unfiltered Output

$R_L = 1.728\ \Omega$

P_{OUT} = Approximately No Load

* Using only output transformer leakage inductance

**** 07/21/95 15:43:17 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(A_PH)

DC COMPONENT = -4.128283E-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.456E+02	1.000E+00	-1.250E+02	0.000E+00
2	1.200E+02	2.739E-01	7.927E-04	-7.881E+01	4.620E+01
3	1.800E+02	8.202E-03	2.373E-05	-6.227E+01	6.273E+01
4	2.400E+02	3.065E-02	8.869E-05	-8.092E+01	4.408E+01
5	3.000E+02	3.808E+00	1.102E-02	-8.470E+01	4.030E+01

6	3.600E+02	2.524E-02	7.305E-05	1.478E+02	2.728E+02
7	4.200E+02	1.991E+00	5.761E-03	2.487E+01	1.499E+02
8	4.800E+02	1.395E-02	4.037E-05	-1.023E+02	2.268E+01
9	5.400E+02	2.710E-02	7.841E-05	-4.516E+01	7.985E+01
10	6.000E+02	2.784E-02	8.055E-05	7.790E+00	1.328E+02
11	6.600E+02	3.372E+00	9.756E-03	6.511E+01	1.901E+02
12	7.200E+02	2.386E-02	6.905E-05	1.560E+02	2.810E+02
13	7.800E+02	2.532E+00	7.327E-03	-5.518E+00	1.195E+02
14	8.400E+02	2.234E-02	6.465E-05	-7.874E+01	4.627E+01
15	9.000E+02	3.313E-02	9.586E-05	-1.986E+01	1.051E+02
16	9.600E+02	2.901E-02	8.394E-05	3.987E+01	1.649E+02
17	1.020E+03	4.891E-01	1.415E-03	3.861E+01	1.636E+02
18	1.080E+03	2.799E-02	8.099E-05	1.743E+02	2.993E+02
19	1.140E+03	4.268E-01	1.235E-03	1.490E+02	2.740E+02
20	1.200E+03	2.739E-02	7.927E-05	-6.753E+01	5.747E+01
21	1.260E+03	3.694E-02	1.069E-04	6.087E+00	1.311E+02
22	1.320E+03	3.030E-02	8.768E-05	7.185E+01	1.969E+02
23	1.380E+03	1.468E+00	4.248E-03	-1.761E+02	-5.112E+01
24	1.440E+03	2.523E-02	7.302E-05	-1.572E+02	-3.217E+01
25	1.500E+03	1.443E+00	4.175E-03	1.154E+02	2.404E+02
26	1.560E+03	2.110E-02	6.107E-05	-2.982E+01	9.518E+01
27	1.620E+03	2.936E-02	8.496E-05	3.067E+01	1.557E+02
28	1.680E+03	2.777E-02	8.034E-05	1.034E+02	2.284E+02
29	1.740E+03	5.147E-01	1.489E-03	1.552E+02	2.802E+02
30	1.800E+03	2.692E-02	7.790E-05	-1.353E+02	-1.026E+01
31	1.860E+03	6.482E-01	1.876E-03	-9.451E+01	3.050E+01
32	1.920E+03	2.868E-02	8.300E-05	-9.217E+00	1.158E+02
33	1.980E+03	3.653E-02	1.057E-04	5.696E+01	1.820E+02
34	2.040E+03	3.170E-02	9.173E-05	1.730E+02	2.980E+02
35	2.100E+03	9.867E+00	2.855E-02	-5.540E+01	6.960E+01
36	2.160E+03	4.112E-02	1.190E-04	-9.178E+01	3.322E+01
37	2.220E+03	9.344E+00	2.704E-02	5.452E+01	1.795E+02
38	2.280E+03	3.799E-02	1.099E-04	5.020E+01	1.752E+02
39	2.340E+03	3.156E-02	9.134E-05	1.156E+02	2.406E+02
40	2.400E+03	2.420E-02	7.004E-05	1.626E+02	2.876E+02
41	2.460E+03	4.423E-01	1.280E-03	9.677E+01	2.218E+02
42	2.520E+03	2.547E-02	7.369E-05	-5.690E+01	6.811E+01
43	2.580E+03	3.029E-01	8.765E-04	-1.537E+02	-2.868E+01
44	2.640E+03	2.392E-02	6.921E-05	5.681E+01	1.818E+02
45	2.700E+03	2.913E-02	8.429E-05	1.273E+02	2.523E+02
46	2.760E+03	2.542E-02	7.356E-05	1.800E+02	3.050E+02
47	2.820E+03	8.136E-01	2.354E-03	-1.149E+02	1.008E+01

48	2.880E+03	2.421E-02	7.007E-05	-4.090E+01	8.410E+01
49	2.940E+03	6.513E-01	1.885E-03	1.733E+02	2.983E+02
50	3.000E+03	2.392E-02	6.921E-05	8.975E+01	2.147E+02
51	3.060E+03	3.183E-02	9.210E-05	1.556E+02	2.806E+02
52	3.120E+03	2.470E-02	7.148E-05	-1.432E+02	-1.823E+01
53	3.180E+03	1.667E-01	4.825E-04	-1.362E+02	-1.122E+01
54	3.240E+03	2.429E-02	7.030E-05	-1.449E+01	1.105E+02
55	3.300E+03	1.513E-01	4.378E-04	-2.478E+01	1.002E+02
56	3.360E+03	2.440E-02	7.061E-05	1.076E+02	2.327E+02
57	3.420E+03	3.307E-02	9.569E-05	-1.797E+02	-5.466E+01
58	3.480E+03	2.619E-02	7.579E-05	-1.180E+02	6.954E+00
59	3.540E+03	5.825E-01	1.685E-03	2.084E+00	1.271E+02
60	3.600E+03	2.419E-02	7.000E-05	1.240E+01	1.374E+02
61	3.660E+03	5.773E-01	1.670E-03	-6.363E+01	6.137E+01
62	3.720E+03	2.227E-02	6.444E-05	1.440E+02	2.690E+02
63	3.780E+03	2.970E-02	8.593E-05	-1.553E+02	-3.029E+01
64	3.840E+03	2.665E-02	7.711E-05	-8.586E+01	3.914E+01
65	3.900E+03	2.459E-01	7.114E-04	-2.573E+01	9.927E+01
66	3.960E+03	2.785E-02	8.058E-05	3.419E+01	1.592E+02
67	4.020E+03	3.180E-01	9.202E-04	8.543E+01	2.104E+02
68	4.080E+03	2.772E-02	8.020E-05	1.641E+02	2.891E+02
69	4.140E+03	3.620E-02	1.048E-04	-1.322E+02	-7.223E+00
70	4.200E+03	2.844E-02	8.231E-05	-3.255E+01	9.245E+01
71	4.260E+03	4.855E+00	1.405E-02	1.242E+02	2.492E+02
72	4.320E+03	3.989E-02	1.154E-04	7.832E+01	2.033E+02
73	4.380E+03	4.731E+00	1.369E-02	-1.259E+02	-9.047E-01
74	4.440E+03	3.292E-02	9.526E-05	-1.501E+02	-2.505E+01
75	4.500E+03	2.981E-02	8.625E-05	-7.511E+01	4.989E+01
76	4.560E+03	2.369E-02	6.856E-05	-2.720E+01	9.781E+01
77	4.620E+03	2.286E-01	6.616E-04	-8.103E+01	4.397E+01
78	4.680E+03	2.385E-02	6.900E-05	1.102E+02	2.352E+02
79	4.740E+03	1.569E-01	4.540E-04	2.905E+01	1.541E+02
80	4.800E+03	2.421E-02	7.004E-05	-1.342E+02	-9.199E+00

TOTAL HARMONIC DISTORTION = 4.795690E+00 PERCENT

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(B_PH)

DC COMPONENT = 3.692429E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.456E+02	1.000E+00	1.150E+02	0.000E+00
2	1.200E+02	2.231E-01	6.456E-04	1.739E+02	5.885E+01
3	1.800E+02	4.344E-02	1.257E-04	7.033E+01	-4.469E+01
4	2.400E+02	9.774E-03	2.828E-05	1.096E+02	-5.414E+00
5	3.000E+02	3.831E+00	1.108E-02	3.502E+01	-7.999E+01
6	3.600E+02	3.108E-02	8.994E-05	1.311E+02	1.608E+01
7	4.200E+02	2.022E+00	5.852E-03	-9.513E+01	-2.101E+02
8	4.800E+02	1.307E-02	3.781E-05	1.057E+01	-1.044E+02
9	5.400E+02	1.612E-02	4.666E-05	1.389E+02	2.384E+01
10	6.000E+02	9.639E-03	2.789E-05	1.729E+02	5.791E+01
11	6.600E+02	3.343E+00	9.672E-03	-1.749E+02	-2.899E+02
12	7.200E+02	8.349E-03	2.416E-05	-9.905E+01	-2.141E+02
13	7.800E+02	2.547E+00	7.370E-03	-1.248E+02	-2.398E+02
14	8.400E+02	1.414E-02	4.090E-05	5.967E+01	-5.535E+01
15	9.000E+02	2.237E-02	6.474E-05	1.477E+02	3.271E+01
16	9.600E+02	1.955E-02	5.656E-05	-1.460E+02	-2.610E+02
17	1.020E+03	4.651E-01	1.346E-03	1.565E+02	4.152E+01
18	1.080E+03	1.379E-02	3.989E-05	-3.693E+01	-1.519E+02
19	1.140E+03	4.474E-01	1.295E-03	2.530E+01	-8.971E+01
20	1.200E+03	2.194E-02	6.348E-05	1.085E+02	-6.479E+00
21	1.260E+03	2.094E-02	6.059E-05	-1.723E+02	-2.873E+02
22	1.320E+03	1.872E-02	5.418E-05	-1.144E+02	-2.294E+02
23	1.380E+03	1.463E+00	4.232E-03	-5.493E+01	-1.699E+02
24	1.440E+03	1.504E-02	4.352E-05	1.493E+01	-1.001E+02
25	1.500E+03	1.473E+00	4.263E-03	-4.595E+00	-1.196E+02
26	1.560E+03	1.311E-02	3.795E-05	1.339E+02	1.886E+01

27	1.620E+03	1.505E-02	4.354E-05	-1.422E+02	-2.572E+02
28	1.680E+03	1.277E-02	3.696E-05	-8.414E+01	-1.991E+02
29	1.740E+03	4.978E-01	1.441E-03	-8.402E+01	-1.990E+02
30	1.800E+03	2.159E-02	6.246E-05	2.293E+01	-9.209E+01
31	1.860E+03	6.335E-01	1.833E-03	1.431E+02	2.806E+01
32	1.920E+03	2.630E-02	7.610E-05	-1.662E+02	-2.813E+02
33	1.980E+03	1.569E-02	4.541E-05	-1.208E+02	-2.358E+02
34	2.040E+03	2.649E-02	7.666E-05	-1.828E+01	-1.333E+02
35	2.100E+03	9.895E+00	2.863E-02	6.467E+01	-5.034E+01
36	2.160E+03	2.923E-02	8.457E-05	9.952E+01	-1.550E+01
37	2.220E+03	9.328E+00	2.699E-02	-6.541E+01	-1.804E+02
38	2.280E+03	1.292E-02	3.738E-05	-5.813E+01	-1.731E+02
39	2.340E+03	1.522E-02	4.403E-05	-6.941E+01	-1.844E+02
40	2.400E+03	2.011E-02	5.819E-05	-2.103E+01	-1.360E+02
41	2.460E+03	4.556E-01	1.318E-03	-1.468E+02	-2.618E+02
42	2.520E+03	6.002E-03	1.737E-05	1.766E+02	6.157E+01
43	2.580E+03	3.261E-01	9.435E-04	8.582E+01	-2.919E+01
44	2.640E+03	1.223E-02	3.539E-05	-1.435E+02	-2.585E+02
45	2.700E+03	1.675E-02	4.847E-05	-5.833E+01	-1.733E+02
46	2.760E+03	1.276E-02	3.693E-05	2.014E+00	-1.130E+02
47	2.820E+03	7.853E-01	2.272E-03	5.720E+00	-1.093E+02
48	2.880E+03	1.094E-02	3.167E-05	1.285E+02	1.345E+01
49	2.940E+03	6.656E-01	1.926E-03	5.541E+01	-5.960E+01
50	3.000E+03	1.139E-02	3.295E-05	-9.378E+01	-2.088E+02
51	3.060E+03	1.630E-02	4.717E-05	-2.479E+01	-1.398E+02
52	3.120E+03	1.334E-02	3.861E-05	4.502E+01	-7.000E+01
53	3.180E+03	1.438E-01	4.162E-04	-2.265E+01	-1.377E+02
54	3.240E+03	6.670E-03	1.930E-05	1.362E+02	2.119E+01
55	3.300E+03	1.620E-01	4.689E-04	-1.550E+02	-2.700E+02
56	3.360E+03	1.561E-02	4.518E-05	-7.465E+01	-1.897E+02
57	3.420E+03	1.601E-02	4.632E-05	4.174E+00	-1.108E+02
58	3.480E+03	1.303E-02	3.770E-05	5.888E+01	-5.613E+01
59	3.540E+03	5.778E-01	1.672E-03	1.249E+02	9.866E+00
60	3.600E+03	1.229E-02	3.556E-05	-1.719E+02	-2.870E+02
61	3.660E+03	6.068E-01	1.756E-03	1.760E+02	6.097E+01
62	3.720E+03	1.318E-02	3.815E-05	-4.214E+01	-1.572E+02
63	3.780E+03	1.566E-02	4.530E-05	3.787E+01	-7.715E+01
64	3.840E+03	1.133E-02	3.279E-05	1.020E+02	-1.298E+01
65	3.900E+03	2.269E-01	6.566E-04	9.638E+01	-1.863E+01
66	3.960E+03	1.704E-02	4.929E-05	-1.697E+02	-2.847E+02
67	4.020E+03	2.980E-01	8.623E-04	-3.910E+01	-1.541E+02
68	4.080E+03	2.314E-02	6.695E-05	7.476E+00	-1.075E+02

69	4.140E+03	1.522E-02	4.404E-05	4.902E+01	-6.599E+01
70	4.200E+03	1.689E-02	4.888E-05	1.403E+02	2.528E+01
71	4.260E+03	4.882E+00	1.413E-02	-1.157E+02	-2.307E+02
72	4.320E+03	2.643E-02	7.649E-05	-9.414E+01	-2.092E+02
73	4.380E+03	4.718E+00	1.365E-02	1.143E+02	-7.276E-01
74	4.440E+03	5.735E-03	1.659E-05	6.956E+01	-4.545E+01
75	4.500E+03	1.407E-02	4.072E-05	9.633E+01	-1.869E+01
76	4.560E+03	2.108E-02	6.099E-05	1.503E+02	3.533E+01
77	4.620E+03	2.365E-01	6.842E-04	3.203E+01	-8.298E+01
78	4.680E+03	5.816E-03	1.683E-05	-2.013E+01	-1.351E+02
79	4.740E+03	1.780E-01	5.150E-04	-9.369E+01	-2.087E+02
80	4.800E+03	1.180E-02	3.415E-05	2.657E+01	-8.844E+01

TOTAL HARMONIC DISTORTION = 4.800307E+00 PERCENT

**** 07/21/95 15:43:17 *** Win32s PSpice 6.1a (August 1994) *** ID# 79034 ****

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

**** FOURIER ANALYSIS TEMPERATURE = 27.000 DEG C

****

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(C_PH)

DC COMPONENT = -3.279596E-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	6.000E+01	3.457E+02	1.000E+00	-4.997E+00	0.000E+00
2	1.200E+02	2.973E-01	8.602E-04	5.544E+01	6.043E+01
3	1.800E+02	3.837E-02	1.110E-04	-1.187E+02	-1.137E+02
4	2.400E+02	2.112E-02	6.109E-05	9.423E+01	9.923E+01
5	3.000E+02	3.835E+00	1.110E-02	1.555E+02	1.604E+02

6	3.600E+02	5.574E-02	1.612E-04	-4.143E+01	-3.644E+01
7	4.200E+02	2.007E+00	5.806E-03	1.441E+02	1.491E+02
8	4.800E+02	1.495E-02	4.325E-05	1.313E+02	1.363E+02
9	5.400E+02	1.107E-02	3.202E-05	1.290E+02	1.340E+02
10	6.000E+02	1.869E-02	5.406E-05	-1.646E+02	-1.596E+02
11	6.600E+02	3.357E+00	9.712E-03	-5.532E+01	-5.032E+01
12	7.200E+02	2.317E-02	6.702E-05	-3.584E+00	1.413E+00
13	7.800E+02	2.566E+00	7.423E-03	1.145E+02	1.195E+02
14	8.400E+02	1.505E-02	4.354E-05	1.398E+02	1.448E+02
15	9.000E+02	1.226E-02	3.547E-05	-1.768E+02	-1.718E+02
16	9.600E+02	9.775E-03	2.828E-05	-1.283E+02	-1.233E+02
17	1.020E+03	4.925E-01	1.425E-03	-8.481E+01	-7.982E+01
18	1.080E+03	1.770E-02	5.119E-05	1.804E+01	2.303E+01
19	1.140E+03	4.126E-01	1.194E-03	-9.535E+01	-9.036E+01
20	1.200E+03	5.709E-03	1.651E-05	1.278E+02	1.328E+02
21	1.260E+03	1.602E-02	4.635E-05	-1.760E+02	-1.710E+02
22	1.320E+03	1.186E-02	3.432E-05	-9.831E+01	-9.332E+01
23	1.380E+03	1.439E+00	4.162E-03	6.428E+01	6.927E+01
24	1.440E+03	1.054E-02	3.049E-05	3.415E+01	3.914E+01
25	1.500E+03	1.457E+00	4.216E-03	-1.256E+02	-1.206E+02
26	1.560E+03	9.276E-03	2.684E-05	1.735E+02	1.785E+02
27	1.620E+03	1.455E-02	4.210E-05	-1.567E+02	-1.517E+02
28	1.680E+03	1.520E-02	4.396E-05	-7.028E+01	-6.528E+01
29	1.740E+03	5.004E-01	1.448E-03	3.391E+01	3.890E+01
30	1.800E+03	1.057E-02	3.057E-05	9.412E+01	9.911E+01
31	1.860E+03	6.174E-01	1.786E-03	2.548E+01	3.047E+01
32	1.920E+03	1.119E-02	3.239E-05	1.043E+02	1.093E+02
33	1.980E+03	2.085E-02	6.033E-05	-1.247E+02	-1.197E+02
34	2.040E+03	7.713E-03	2.231E-05	3.514E+01	4.014E+01
35	2.100E+03	9.871E+00	2.856E-02	-1.752E+02	-1.702E+02
36	2.160E+03	1.372E-02	3.968E-05	6.354E+01	6.854E+01
37	2.220E+03	9.346E+00	2.704E-02	1.746E+02	1.796E+02
38	2.280E+03	3.608E-02	1.044E-04	-1.497E+02	-1.447E+02
39	2.340E+03	1.646E-02	4.762E-05	-5.979E+01	-5.479E+01
40	2.400E+03	4.330E-03	1.253E-05	-5.943E-02	4.938E+00
41	2.460E+03	4.728E-01	1.368E-03	-2.362E+01	-1.862E+01
42	2.520E+03	2.242E-02	6.486E-05	1.107E+02	1.157E+02
43	2.580E+03	3.128E-01	9.049E-04	-3.762E+01	-3.262E+01
44	2.640E+03	1.315E-02	3.803E-05	-1.044E+02	-9.939E+01
45	2.700E+03	1.257E-02	3.635E-05	-4.526E+01	-4.026E+01
46	2.760E+03	1.267E-02	3.666E-05	-2.057E+00	2.940E+00
47	2.820E+03	7.921E-01	2.291E-03	1.236E+02	1.286E+02

48	2.880E+03	1.361E-02	3.937E-05	1.476E+02	1.526E+02
49	2.940E+03	6.795E-01	1.966E-03	-6.668E+01	-6.168E+01
50	3.000E+03	1.257E-02	3.637E-05	-8.706E+01	-8.207E+01
51	3.060E+03	1.553E-02	4.492E-05	-2.390E+01	-1.890E+01
52	3.120E+03	1.166E-02	3.372E-05	2.732E+01	3.232E+01
53	3.180E+03	1.712E-01	4.953E-04	9.414E+01	9.913E+01
54	3.240E+03	1.876E-02	5.428E-05	1.755E+02	1.805E+02
55	3.300E+03	1.323E-01	3.827E-04	8.589E+01	9.089E+01
56	3.360E+03	8.824E-03	2.553E-05	-6.828E+01	-6.328E+01
57	3.420E+03	1.713E-02	4.956E-05	-3.247E+00	1.751E+00
58	3.480E+03	1.320E-02	3.818E-05	6.498E+01	6.997E+01
59	3.540E+03	5.555E-01	1.607E-03	-1.169E+02	-1.119E+02
60	3.600E+03	1.197E-02	3.464E-05	-1.631E+02	-1.581E+02
61	3.660E+03	5.891E-01	1.704E-03	5.369E+01	5.868E+01
62	3.720E+03	9.266E-03	2.681E-05	-2.735E+01	-2.235E+01
63	3.780E+03	1.489E-02	4.306E-05	1.085E+01	1.584E+01
64	3.840E+03	1.550E-02	4.485E-05	8.838E+01	9.337E+01
65	3.900E+03	2.294E-01	6.636E-04	-1.488E+02	-1.438E+02
66	3.960E+03	1.408E-02	4.073E-05	-1.165E+02	-1.115E+02
67	4.020E+03	2.872E-01	8.309E-04	-1.533E+02	-1.483E+02
68	4.080E+03	1.125E-02	3.255E-05	-7.076E+01	-6.576E+01
69	4.140E+03	2.099E-02	6.072E-05	4.687E+01	5.187E+01
70	4.200E+03	1.187E-02	3.434E-05	1.577E+02	1.627E+02
71	4.260E+03	4.862E+00	1.406E-02	4.502E+00	9.500E+00
72	4.320E+03	1.412E-02	4.084E-05	-1.159E+02	-1.109E+02
73	4.380E+03	4.738E+00	1.371E-02	-5.673E+00	-6.760E-01
74	4.440E+03	2.873E-02	8.312E-05	2.264E+01	2.764E+01
75	4.500E+03	1.603E-02	4.637E-05	1.124E+02	1.174E+02
76	4.560E+03	2.787E-03	8.062E-06	1.717E+02	1.767E+02
77	4.620E+03	2.566E-01	7.422E-04	1.570E+02	1.620E+02
78	4.680E+03	2.056E-02	5.948E-05	-8.220E+01	-7.720E+01
79	4.740E+03	1.615E-01	4.673E-04	1.411E+02	1.461E+02
80	4.800E+03	1.363E-02	3.942E-05	6.236E+01	6.736E+01

TOTAL HARMONIC DISTORTION = 4.798688E+00 PERCENT

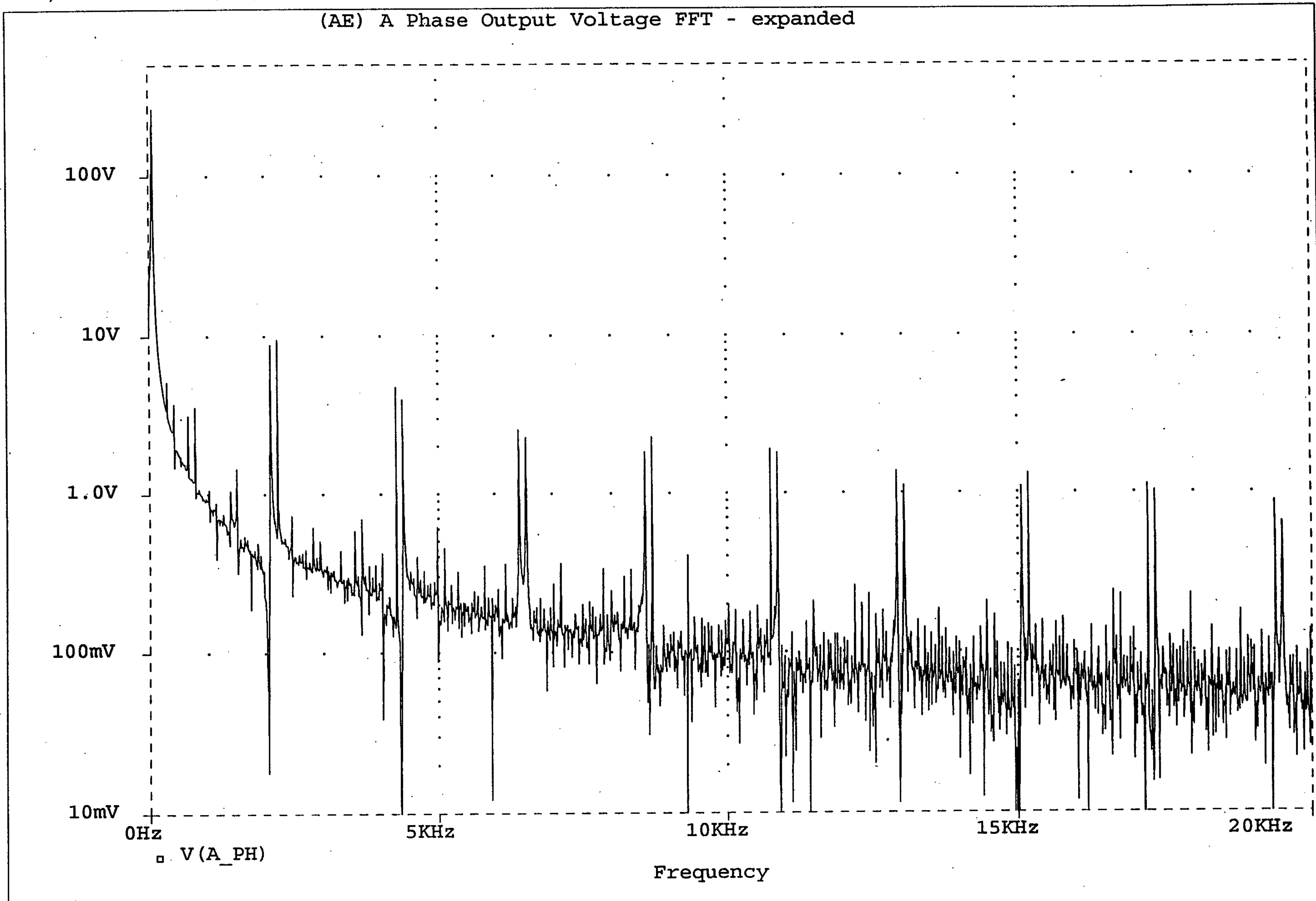
JOB CONCLUDED

TOTAL JOB TIME 3137.21

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17

Temperature: 27.0



Date: July 21, 1995

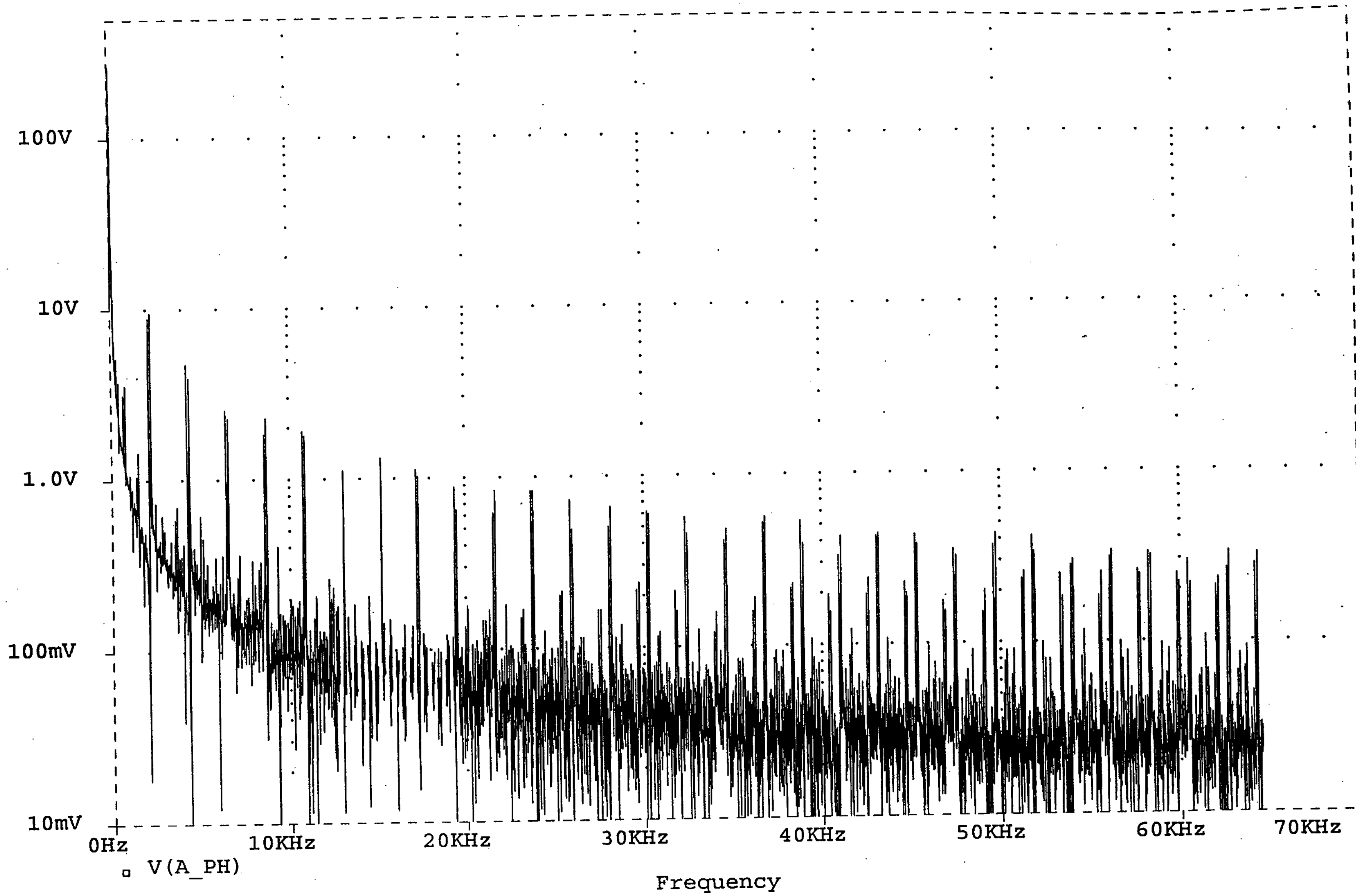
Page 1

Time: 16:39:33

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17 Temperature: 27.0

(AD) A Phase Output Voltage FFT

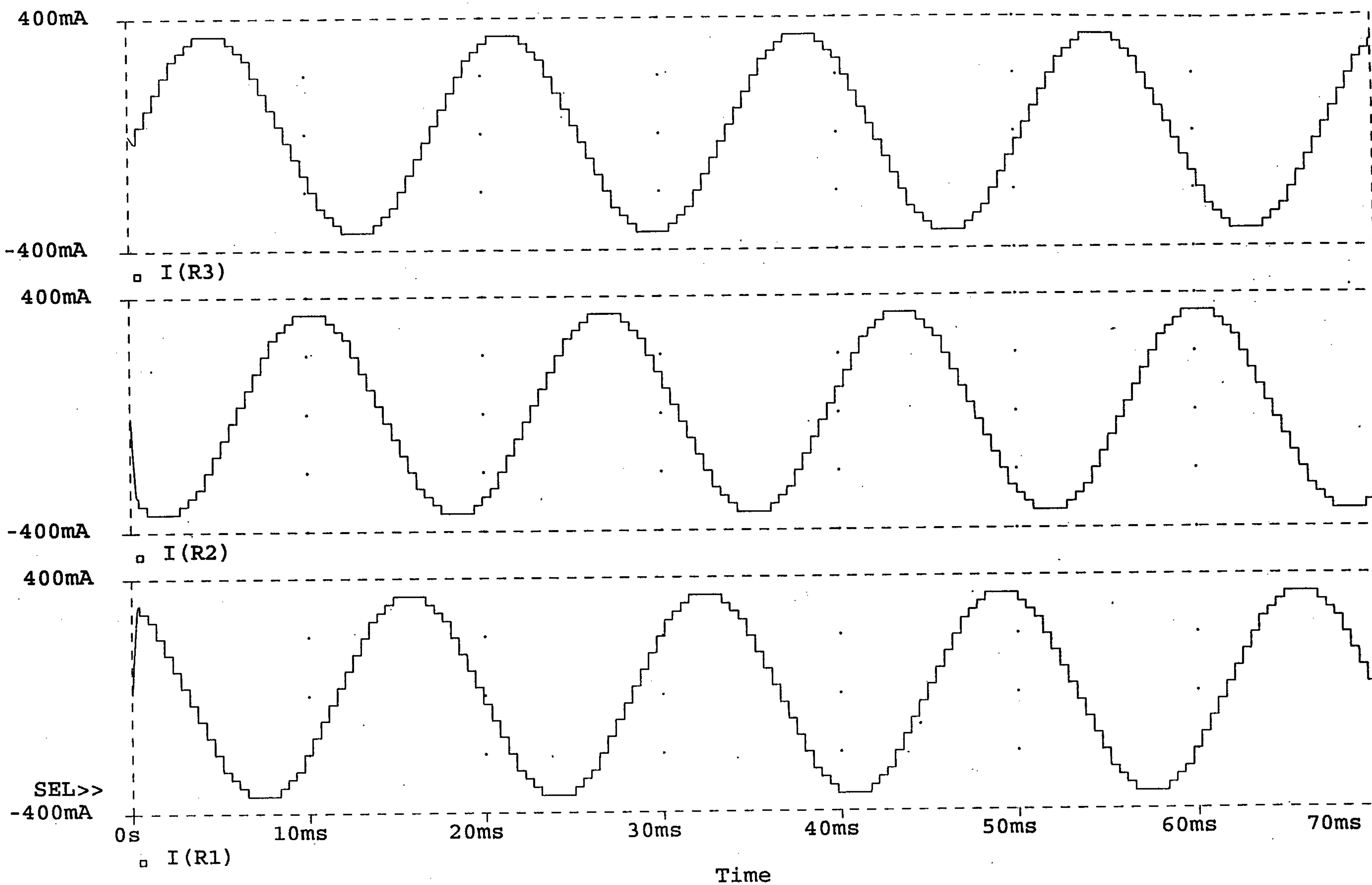


Date: July 21, 1995 Page 2 Time: 16:39:54

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17 Temperature: 27.0

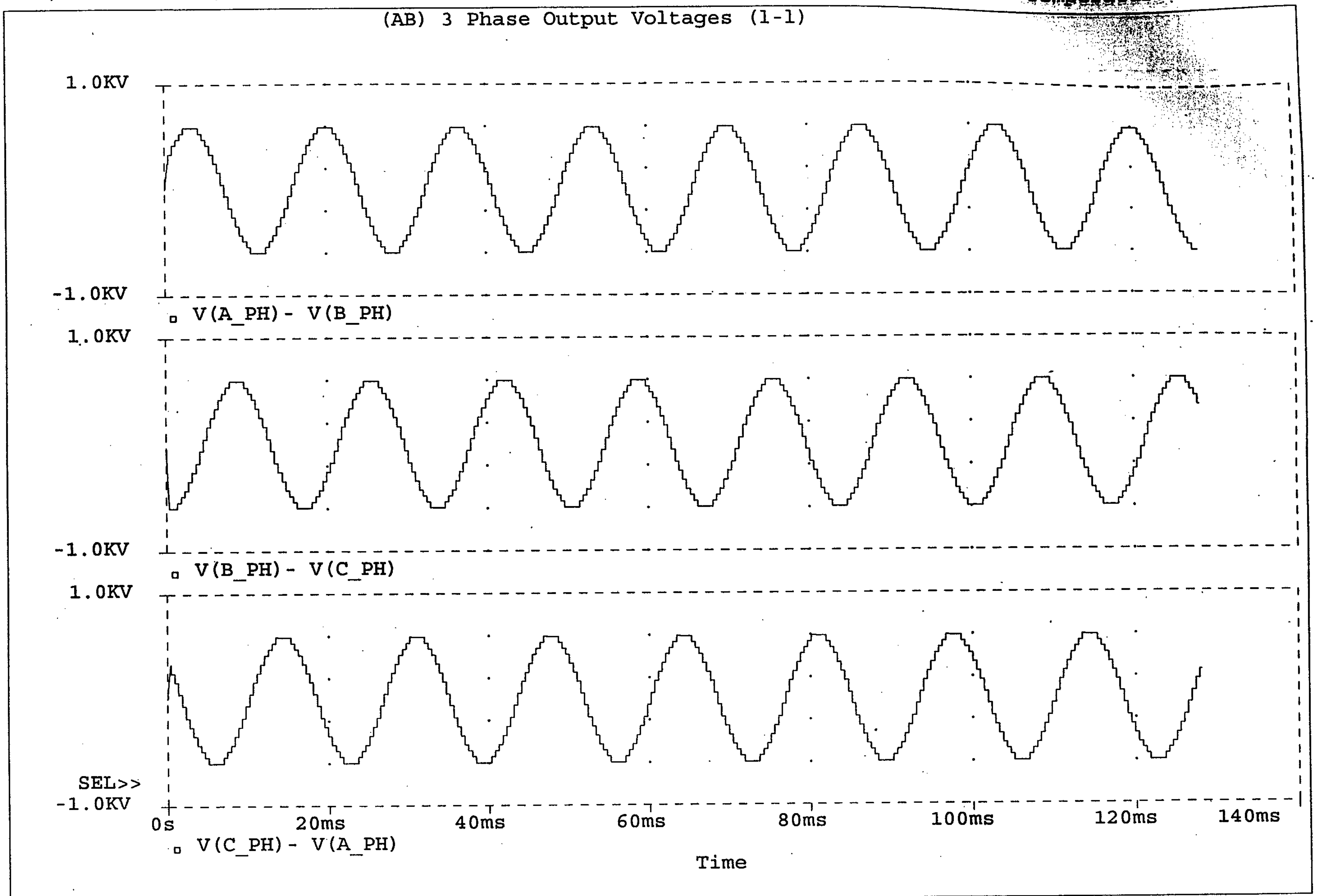
(AC) 3 Phase Output Currents



Date: July 21, 1995 Page 3 Time: 16:40:54

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17 Temperature: 27.0

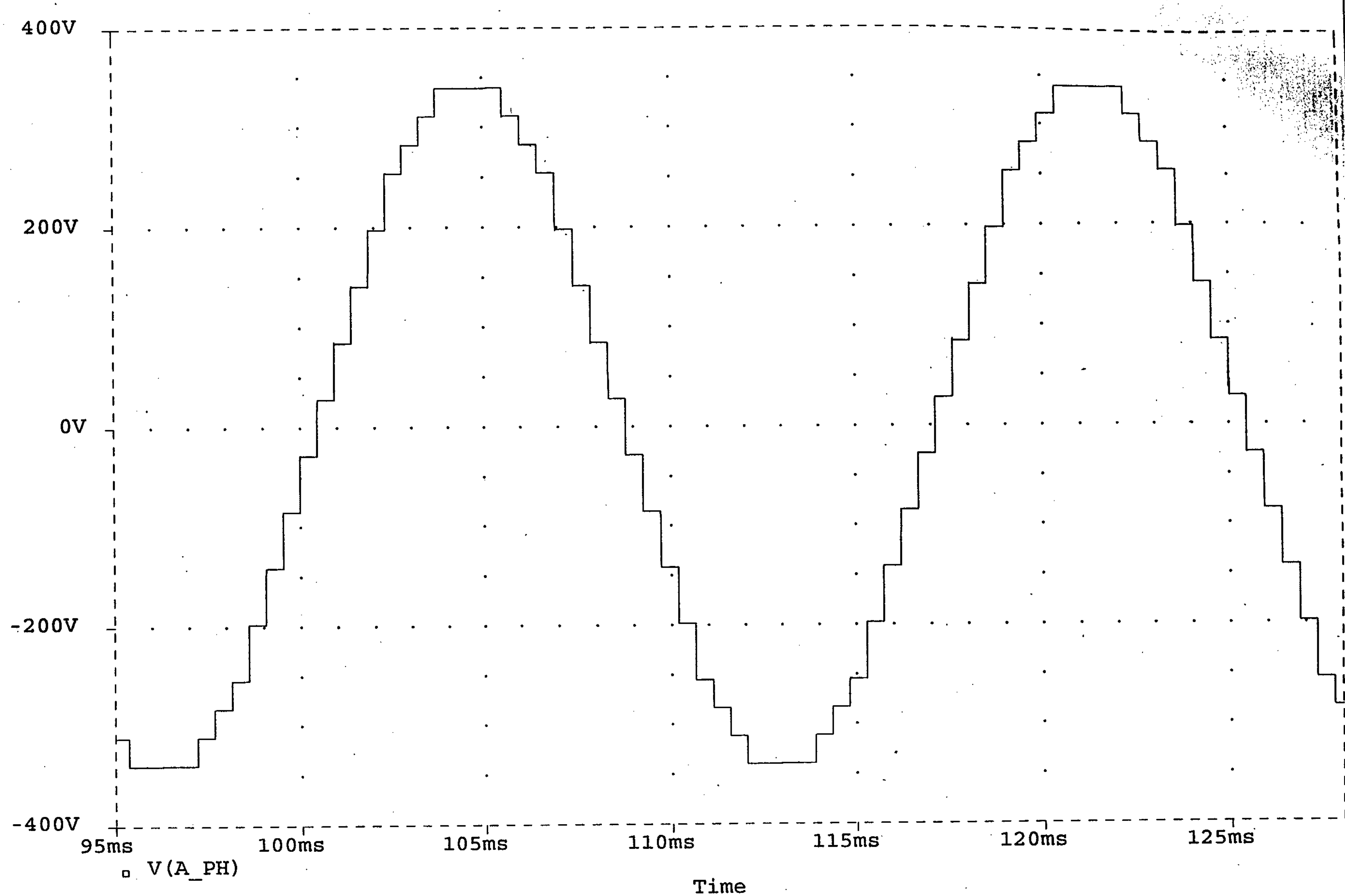


Date: July 21, 1995 Page 4 Time: 16:41:39

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17 Temperature: 27.0

(AA) A Phase Output Voltage - expanded



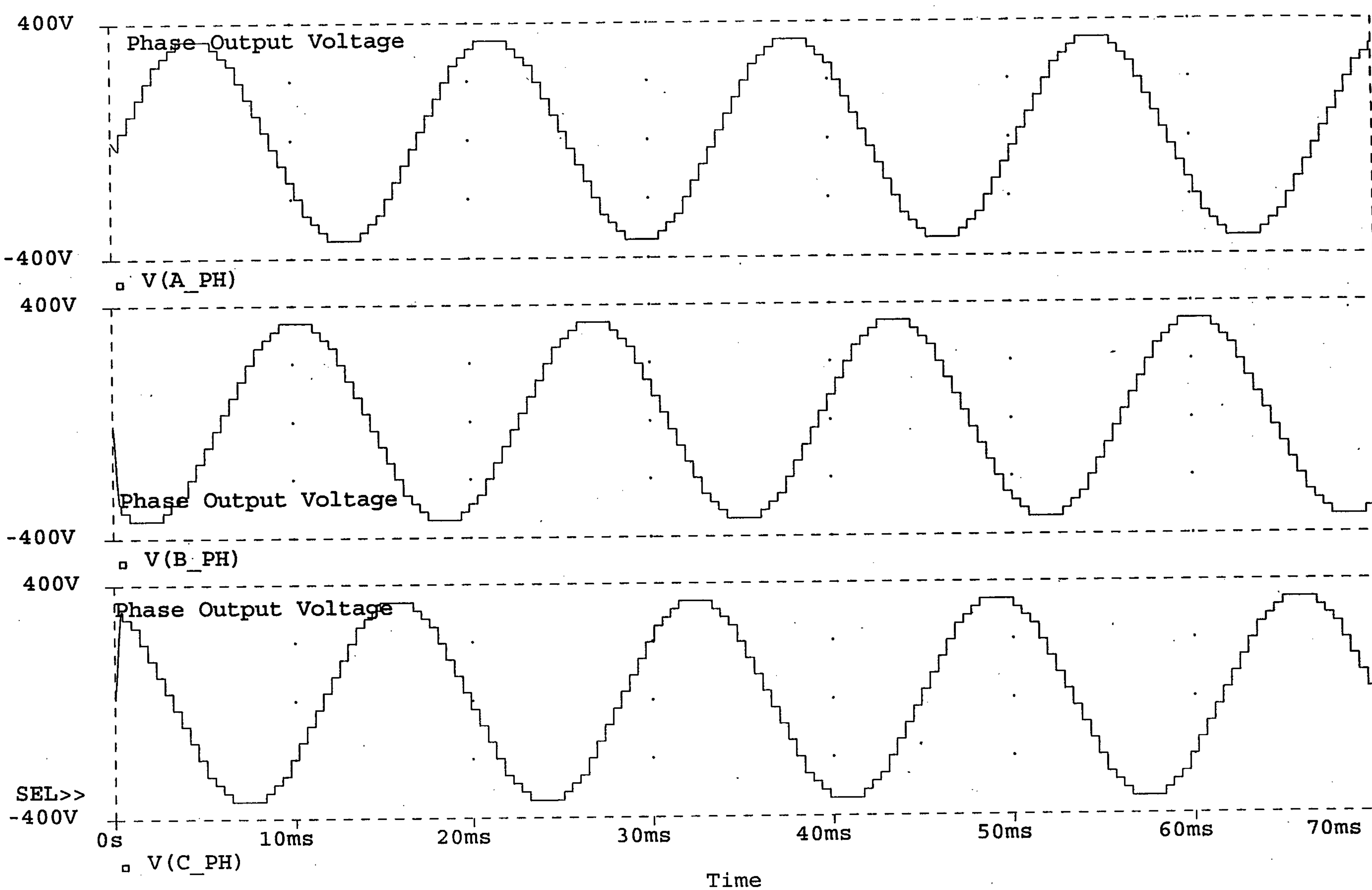
Date: July 21, 1995 Page 5 Time: 16:42:47

* C:\DATA\PSPICE\3PH60HZ\3PH-B9.SCH

Date/Time run: 07/21/95 15:43:17

Temperature: 27.0

(Z) 3 Phase Output Voltages (1-n)



Date: July 21, 1995

Time: 16:42:59

OUTPUT WAVEFORMS

for

Various Summing Converter

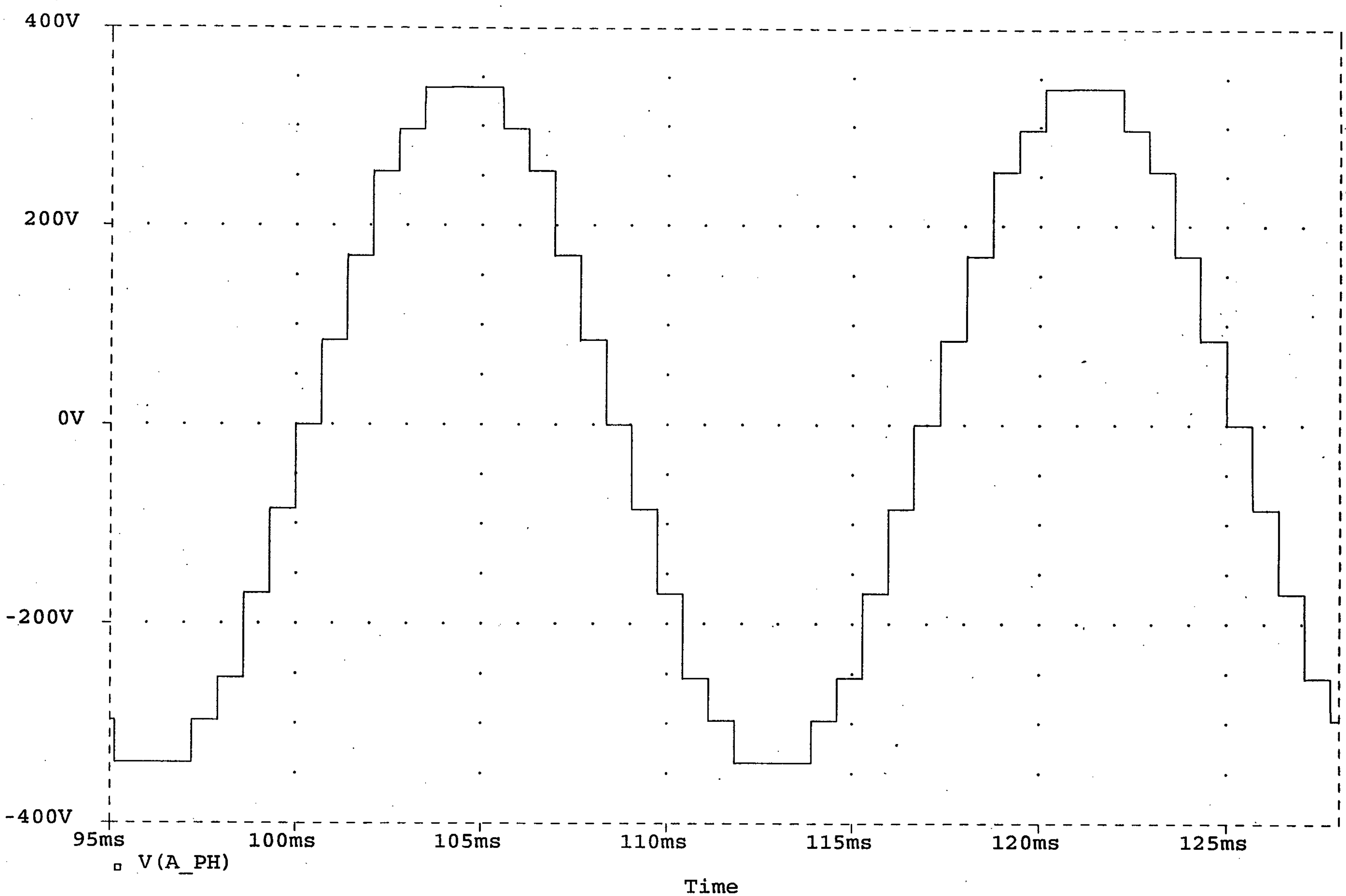
Bridge Output Configurations

* C:\DATA\PSPICE\3PH60HZ\24-STEP\3PH-B5.SCH

Date/Time run: 08/08/95 15:58:30

Temperature: 27.0

(AQ) A Phase Output Voltage - expanded



Date: August 08, 1995

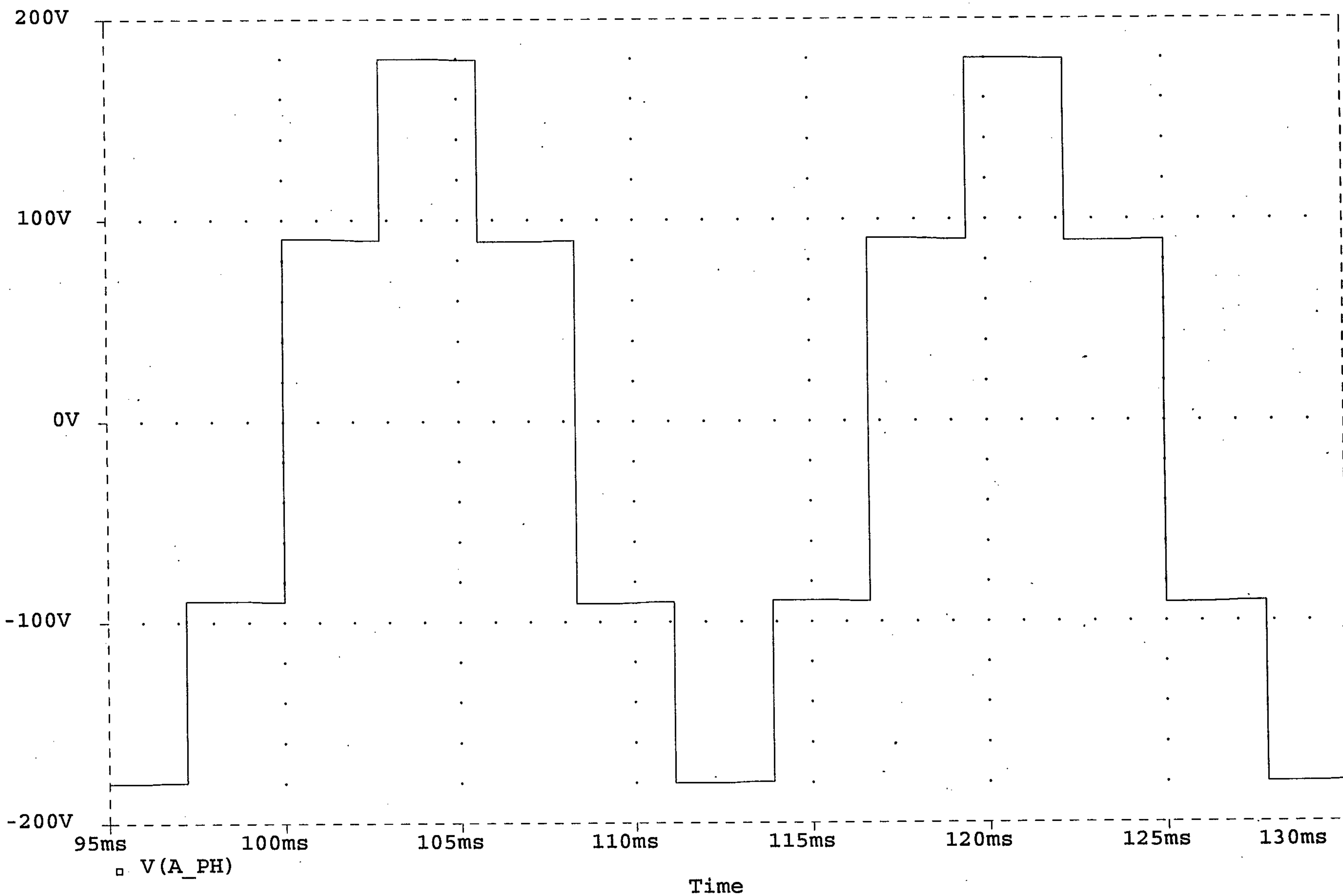
Page 1

Time: 16:22:13

* C:\DATA\PSPICE\3PH60HZ\06-STEP\3PH-B1.SCH

Date/Time run: 09/13/95 15:34:05 Temperature: 27.0

(B) C:\DATA\PSPICE\3PH60HZ\06-STEP\3PH-B1.DAT



Date: September 13, 1995 Page 1 Time: 15:35:23

Appendix F Power Semiconductor Information

POWEREX

Powerex, Inc., 200 Hillis Street, Youngwood, Pennsylvania 15697-1800 (412) 925-7272
Powerex, Europe, S.A. 428 Avenue G. Durand, BP107, 72003 Le Mans, France (43) 41.14.14

Figure 1.1 Application for Power Devices